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SEWER FLOW MEASUREMENT
A STATE-OF-THE-ART ASSESSMENT

Municipal Environmental Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

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SEWER FLOW MEASUREMENT - A STATE-OF-THE-ART ASSESSMENT

by

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FOREWORD

Man and his environment must be protected from the adverse effects of pesticides, radiation, noise, and other forms of pollution, and the unwise management of solid waste. Efforts to protect the environment require a focus that recognizes the interplay between the components of our physical environment--air, water, and land. The Municipal Environmental Research Laboratory contributes to this multidisciplinary focus through programs engaged in

- studies on the effects of environmental contaminants on the biosphere, and
- a search for ways to prevent contamination and to recycle valuable resources.

The deleterious effects of storm and combined sewer overflows upon the nation's waterways have become of increasing concern in recent times. Efforts to alleviate the problem depend upon accurate characterization of these flows in both a quantity and quality sense. This report presents a state-of-the-art survey of flow measuring devices and techniques that either are, or might be, appropriate for the quantitative measurement of stormwater and combined sewer flows as well as other wastewater discharges, and will be of interest to those who have a requirement for the measurement of such flows.

ABSTRACT

A brief review of the characteristics of storm and combined sewer flows is given, followed by a general discussion of the need for such flow measurement, the types of flow data required, and the time element in flow data. A discussion of desirable flow measuring equipment characteristics presents both equipment requirements as well as desirable features and includes an equipment evaluation sheet that can be used for a particular application.

A compendium of over 70 different generic types of primary flow measurement devices, arranged according to the fundamental physical principles involved, is presented along with evaluations as to their suitability for measurement of storm or combined sewer flows. To illustrate the implementation of the physical principles, a number of commercially-available devices for flow measurement are briefly described.

A review of selected U.S. Environmental Protection Agency project experience in flow measurement is presented along with a summary of current and on-going research efforts. Some thoughts on future areas of research and development are also given. This report was submitted in fulfillment of Contract Number 68-03-0426 under the sponsorship of the Office of Research and Development, U.S. Environmental Protection Agency. Work was completed in December 1974.

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ACKNOWLEDGMENTS

The cooperation and support of the commercial manufacturers and suppliers of flow measuring equipment and their representatives is acknowledged with sincere thanks. They supplied information about their current products and proposed new developments, took time to answer questions and provide operational insights, and made the preparation of Section VII of this report possible. All equipment illustrations were provided by the respective manufacturers, and appreciation for their use in this report is hereby acknowledged.

Appreciation must also be expressed to all of the project engineers and research workers who took time to discuss various aspects of their work, to share insights and field experiences, and to offer suggestions about the use of certain equipment.

Finally, the support of this effort by the Storm and Combined Sewer Section (Edison, New Jersey), Wastewater Research Division, Municipal Environmental Research Laboratory, Cincinnati, Ohio, and especially Mr. David J. Cesareo, Project Officer, and the other manuscript reviewers is acknowledged with gratitude.

SECTION I

CONCLUSIONS

1. A flowmeter is one tool of several that must be employed for the characterization of a wastewater stream. Its selection must be based upon consideration of the overall flow measurement program to be undertaken, the nature of the flows to be measured, the physical characteristics of the flow measurement sites, and the degree of accuracy required, among other factors.

2. In view of the large number of highly variable parameters associated with the storm and combined sewer application, no single flowmeter can exist that is universally applicable with equal efficacy. Some requirements are conflicting, e.g., an open drainage ditch versus a closed conduit deep underground, and a careful series of trade-off studies is required in order to arrive at a "best" selection for a particular program and site.

3. There are over 70 generic devices and methods that can be used for determining wastewater flows, and they were reviewed and discussed.

4. The proper selection of flow measurement sites can be as important as the selection of methods and equipment. A clear understanding of the data requirements and ultimate use is necessary, as is a familiarity with the sewer system to be examined.

5. Of the over 120 prospective manufacturers of liquid flow measuring equipment which were contacted, none has a flow measurement product line that is specifically designed for the storm and combined sewer application.

6. Where large flows are to be measured with fairly high accuracy, considerable expense in terms of initial equipment cost, site preparation and installation, and operator training and maintenance is involved; fifty to one hundred thousand dollars should not be considered atypical.

7. There are measurement sites where no presently available equipment can operate unattended for long at a high degree of accuracy (better than ±5% of full scale).

8. The most consistently reliable flow measurement data have been taken at sites where the equipment has been calibrated in place over the entire range of flows anticipated.

9. Field experience in wastewater flow measurement was reviewed, and in most instances errors of greater than 10% seem to be the rule. It is not at all uncommon to find readings that differ from spot field checks by from 50 to 200 percent. Some wastewater discharge data are of such poor quality as to be virtually useless.

10. Flow measurement research efforts within the United States were reviewed. Very few of those outside the USEPA are addressed to the storm and combined sewer problem as presented here, and it would appear that few, if any, that are not so oriented will produce technology fall-outs that will benefit the solution of the problem at hand.

11. The technological state-of-the-art, especially in electronics, is advancing very rapidly at the present time, and capabilities are emerging that until now were either impossible or prohibitively expensive. Examples include improved pressure sensors, solid state and integrated circuitry advances (and price reductions) that facilitate control and computational functions, quartz crystal timers that offer accuracy improvements measured in orders of magnitude, improvements in electronic recorders, etc. As a result, both new products and improvements to old ones are continually appearing.

SECTION II

RECOMMENDATIONS

1. It is recommended that flow measurement accuracy requirements be very carefully considered with an eye to optimizing the accuracy of determination of total pollutant discharge. Very high accuracies over very wide ranges may not be necessary for all purposes and will certainly be expensive to achieve.

2. Where possible, it is recommended that flow measurement equipment be calibrated in place at the site where the data are to be collected. Maintenance should be performed such that conditions do not deviate greatly from those at the time of calibration.

3. Use and maintenance of complex, sophisticated flow measurement equipment should not be entrusted to well-meaning but untrained personnel. Proper training of operator personnel is recommended as it will produce long-term benefits.

4. It is recommended that the flow measurement site be chosen with great care. It can be as poor an error in judgement to choose a site that will not yield the desired data simply because of equipment availability as it is to attempt to apply the wrong equipment at a site that is truly important.

5. In view of the immediate requirements for storm and combined sewer discharge data for surveys, computer model calibration and verification, infiltration/inflow studies, and the like, the most urgent need is for suitable portable devices that are capable of unattended operation. It is strongly recommended that a program to develop such devices be initiated with special emphasis on:

    - Automated Chemical Dilution Devices
    - Ultrasonic Devices
    - Hybrid Flumes

6. There has been very little opportunity to evaluate flow measurement equipment suitable for storm and combined sewer applications in a side-by-side fashion under somewhat controlled conditions. It is strongly recommended that a suitable facility be identified and used to gather comparative data with emphasis on the more promising portable devices.

7. There are a number of flow measurement devices that have either recently become available or are about to be introduced and that offer considerable promise in a storm and combined sewer application. It is recommended that a program of demonstration testing be initiated to include such devices as:

    - Venturi Meter/Flumes
    - Combination Thermal Flowmeters
    - High Range Open Flow Nozzles

8. This study was essentially limited to developments and practices within the United States. It is recommended that a survey of foreign research and development activities and storm and combined sewer flow measurement practices be conducted.

9. Because of the burgeoning nature of the present state of the art and increasing concern over environmental contamination caused by storm and combined sewer discharges, this report should not be considered a final, enduring document. It is recommended that it be expanded and updated within two years.

SECTION III

INTRODUCTION

Since almost the beginning of civilization, man has recognized the need to determine liquid flow rates, quantities, or stages, and his first efforts were probably directed towards survival during floods and transportation by water craft. Demands for water supply, irrigation, navigation, and waterpower all accentuated the need for flow measurement. It is known that the ancient Babylonians and Egyptians used some means of water accounting to individual land holders from their extensive irrigation systems. The procedures used were possibly taken from methods used earlier in eastern Asia.

The River Nile of Egypt has probably been studied for a longer period of time than any other river in the world. The crops of the Nile Valley are dependent upon annual flooding by the river, and thus, annual yields are proportional to fluctuation in stage. In view of this, taxes were levied based upon maximum flood height. An interesting compilation of data concerning flood records of the Nile has been prepared by Jarvis (1). Mention of the annual rises of the Nile date back to between 3000 and 3500 B.C., and known flood marks extend as far back as approximately 1800 B.C.

One of the most complete records of early flow measurement systems is that by Sextus Julius Frontinus (2), who was the Water Commissioner of Rome in the latter part of the first century. The quantity of water delivered to each user in the Roman system was determined entirely on the area of spouts through which the flow was discharged; thus, these could be considered as early forms of flow nozzles.

The earliest attempts at flow velocity measurement were undoubtedly made by timing the travel of floating debris over some measured distance. Hero of Alexandria's proposal, which was written about 62 A.D., called for using a sun dial for timing his operation. In the 15th Century, Leonardo da Vinci offered an improvement by attaching an inflated pig's bladder to one end of a pole and a stone to the other, thus achieving an integrating float of sorts. Frazier (3) provides an interesting account of a physician's plan for a deflection water current meter, circa 1610. In the middle of the 17th Century, Evangelista Torricelli developed the relation that the rate at which water was discharged from an orifice varied with the square root of the height of the water surface in the supply tank. Subsequent improvements in the state of the art included Henri Pitot's impact tube developed in 1732, Reinhard Woltman's propeller-type current meter invented around 1790, and the work of Giovanni Venturi on the relations between the velocities and pressures of fluids flowing through converging and diverging tubes reported in 1797.

The history of improvements in flow measurement devices/techniques is far too extensive to be reported here. The reader interested in the subject is referred to some of the selected additional references listed in Section XI. It suffices to say that today we have a plethora of liquid flow measurement devices and techniques available, and it is to them that the remainder of this report will be directed.

PURPOSE AND SCOPE

Among man's first waterworks projects were aqueducts to convey water into his cities for consumption and sewers to collect and dispose of nuisance stormwater. As early urbanization continued, these first storm drains also became the transport media for domestic wastewater and, in effect, the first combined sewers. For convenience and expediency, these sewers simply emptied into the nearest natural watercourse. As urbanization continued, the dry-weather flow in these sewers became a public nuisance, and wastewater treatment was born. Sanitary engineering practices and procedures were developed, all based upon characterizing and treating this dry-weather or sanitary sewage flow. The construction of separate storm and sanitary sewer systems in many cities was merely an extension of this trend. The pollutional characteristics of stormwater were unrecognized, and it continued to be simply discharged into the nearest natural stream.

The phenomenal growth of urban areas in recent times and the rapid expansion of industrial operations to meet society's ever increasing demands for more goods, energy, etc., have heightened the pollutional potential of man's existence and have contributed to his increasing awareness of and concern for his environment. One of the impacts of the population explosion is that sanitary engineering practices that appeared tolerable even as recently as a few decades ago are no longer acceptable today in many locales. The pollutional effects of stormwater and combined sewer overflows on receiving water quality are becoming less and less tolerable and a research program to mitigate or ameliorate the situation has been underway at the USEPA (and its predecessor agencies) for the last several years.

In order to characterize these stormwater and combined sewer overflows and to facilitate the development, demonstration, and evaluation of treatment and control systems for combating the problem, it is necessary to have available accurate and reliable means of determining the quantity and quality of the flows in question. Both the quantity and quality of urban stormwater runoff are highly variable and transient in nature, being dependent upon meteorological and climatological factors, topography, hydraulic characteristics of the surface and subsurface conduits, the nature of the antecedent period, and the land use activities and housekeeping practices employed. Conventional flow measurement devices and techniques have been developed mainly for the relatively steady-state flows as found in irrigation canals, sanitary sewers, and large streams and not for the highly varying surges encountered in storm and combined sewers.

This report is intended to present a current review of the state of the art and assessment of flow measurement devices and techniques. These are described and evaluated in terms of their suitability for use in storm and combined sewer applications. However, a device or technique which is suitable for such use will most likely suffice for any other wastewater flow measurement application as well. By collecting and presenting such a review, it is hoped that shortcomings and limitations of some extant devices and techniques for storm and combined sewer applications can be overcome and that this report can serve as a springboard for improvements.

GENERAL NATURE OF STORM AND COMBINED SEWER FLOWS

Storm Sewer Flows

Although storm sewers are basically designed to carry storm runoff, during periods of no rainfall they often carry a small but significant flow (dry weather flow). This may be flow from ground water, or "base flow", which gains access to the sewer from unpaved stream courses. Such base flow may appear as runoff from parks or from suburban areas where there are open drains leading to the storm sewer. Unfortunately, much of the dry weather flow in storm sewers is composed of domestic sewage or industrial wastes or both. Where municipal ordinances concerning connections to sewers are lax or are not rigidly enforced, it appears reasonably certain that unauthorized connections to storm sewers will appear. In some cases, the runoff from septic tanks is carried to them. Connections for the discharge of swimming pools, foundation drains, sump pumps, cooling water, and pretreated industrial process water to storm sewers are permitted in many municipalities and contribute to flow during periods of no rainfall. In some areas, sewers classed as storm sewers are, in fact, sanitary or industrial waste sewers due to the unauthorized or inappropriate connections made to them. This may become so aggravated that a continuous flow of sanitary or industrial wastes, or both, flows into the receiving stream.

The "dry-weather" portion of storm sewer flow may vary significantly with time. Probably the most steady flow, and constant character of pollutants therein, occurs in storm sewers when all flow is base flow derived from ground water. Because of the slow movement of water through the ground, changes in flow and concentration of pollutants occur only during relatively long time periods. Where unauthorized connections of domestic sewage and industrial waste lines to storm sewers are found, rapid fluctuations with time may occur. The domestic sewage constituent varies with time of day, with season of year, and probably over long-term periods. Industrial wastes vary with specific processes and industries. Very rapid changes may occur with plant shift changes and with process dynamics. Conditions on weekends and holidays may be very different from those on regular work days.

Storm runoff is the excess rainfall which runs off the ground surface after losses resulting from infiltration to ground water, evaporation, transpiration by vegetation, and ponding occur. A small portion of the rainfall is held in depression storage, resulting from small irregularities in the land surface. The quantity, or rate of flow, of storm runoff varies with intensity, duration, and areal distribution of rainfall; character of the soil and plant life; season of the year; size, shape and slope of the drainage basin; and other factors. Ground seepage loss varies during the storm, becoming less as the ground absorbs the water. The period of time since the previous, or antecedent, rainfall significantly affects the storm runoff.

In general, storm runoff is intermittent in accordance with the rainfall pattern for the area. It is also highly variable from storm to storm and during a particular storm. The time-discharge relationship, or hydrograph, of a typical storm, with its synchronous time-precipitation relationship, or hyetograph, is illustrated in Figure 1. The meanings of various parameters given in the figure are:

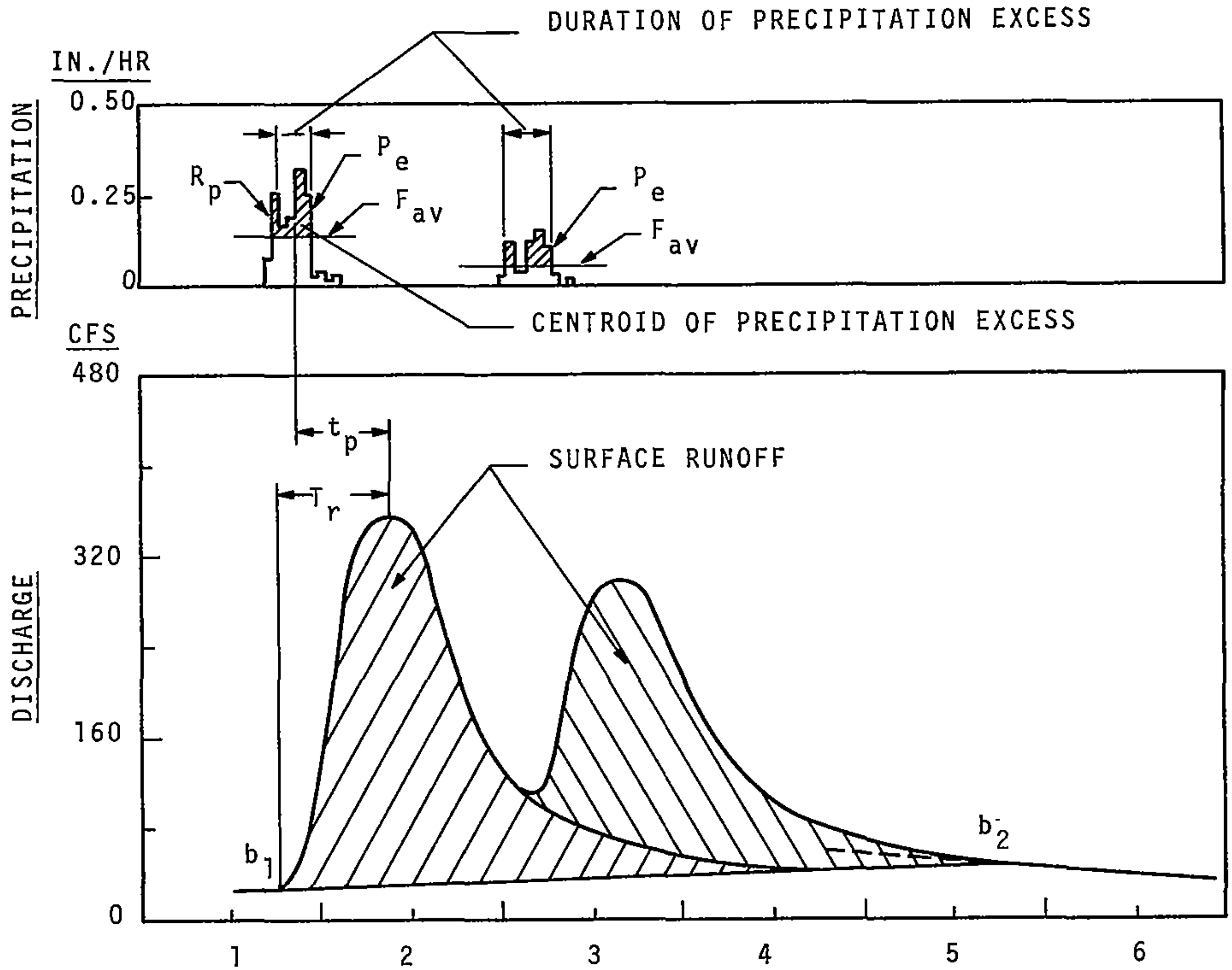
R_p - Rainfall retained on the permeable portion of the drainage basin, and not available for runoff.

P_e - Precipitation in excess of that infiltrated into the ground, plus that retained on the surface. Equals the volume of flood runoff.

F_{av} - Average infiltration of the ground during the storm. Infiltration capacity decreases as the storm progresses.

T_r - Period of rise from the beginning of storm runoff to peak of the hydrograph.

T_p - Time from center of gravity of rainfall excess to the hydrograph peak (lag time).



LEGEND: 1 INCH = 2.54 CM
1 CUBIC FOOT = 28.3 LITERS

APRIL, 1959

Figure 1. Typical Storm Hyetograph and Hydrograph

b_1, b_2 - Base line separating groundwater discharge from surface runoff.

The total volume of runoff for a particular storm is represented by the areas between the base line and the hydrograph.

To illustrate some of the problems in measuring storm runoff in small basins, peak flows exceeding 85 cubic meters per second per 260 hectares (3,000 cfs per square mile) have been observed. Lag times (t_p), for example, of 15 minutes to a hydrograph peak of about 28 cubic meters per second (1000 cfs) from a 600-hectare (2.3 sq mi) area are not uncommon. With rapid changes in the flow such as this, only those flow measurement methods which are responsive to such changes can be used. The high rates of flow, with accompanying high velocities, further limit the usable flow measuring equipment methods.

The maximum rate of flow in an underground storm sewer is governed by its design capacity. This capacity is based on the flow due to a storm occurring, on the average, once in a selected number of years (recurrence interval). Usually, a recurrence interval not greater than 10 years is selected for the design of underground storm sewers. As a result, the design capacity of the sewer is sometimes exceeded, resulting in surcharging and flooding of the overlying surface. Under these conditions, measurement of surface flow must be added to measurement of surcharged flow in the sewer to obtain total flow.

The poor quality of stormwater draining from the urban environment has a significant effect on the choice of suitable flow measurement equipment and methods. Washings from the sidewalks, streets, alleys, and catch basins are a part of the runoff and include significant amounts of human and animal refuse. In industrial areas, chemicals, fertilizers, coal, ores, and other products are stockpiled exposed to rainfall, so that a significant quantity of these materials appears in the runoff. Extreme quantities of organic materials such as leaves and grass cuttings often appear in storm sewers. Often during storms large boards, limbs, rocks, and every imaginable kind of debris appear in the sewers, probably as a result of breaks in the sewers or accessory equipment designed to screen out the larger items.

Observation and experience have demonstrated that the heaviest concentration of suspended solids during periods of storm runoff usually occurs during the early part of the storm. At this time, the stage is rising, and accumulated dry-weather solid residue is being flushed from the sewers and washed and eroded from the tributary land areas. As runoff recedes, the sewer and land area surfaces exposed to flow are reduced; the flow velocities which serve to flush and erode are decreased; and the more easily dislodged solids have been acted upon.

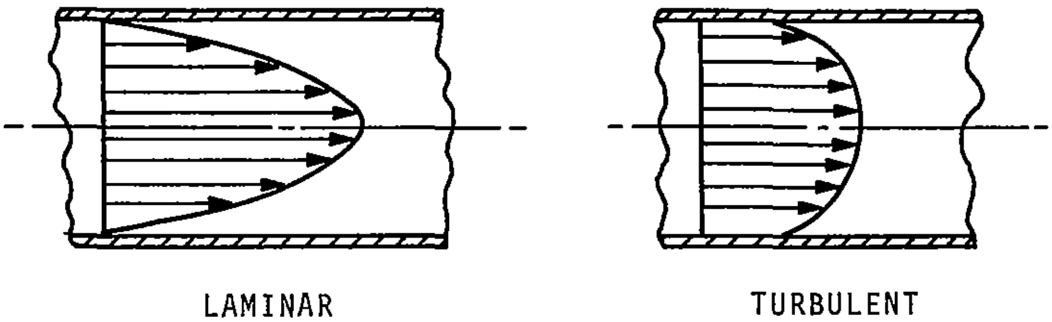
This pattern of variation may not occur during a period of storm runoff which immediately follows a previous storm runoff period because the land surface and sewer lines are relatively clean.

Pollutants which may be injurious to equipment, and are derived from point sources such as those from stockpile drainage, vary at the sampling location with time of travel from the source to the point of observation. Maximum concentration may occur after the peak of storm runoff. It is conceivable that there would be no contribution from some point sources during a specific storm because of areal variation of rainfall in the basin.

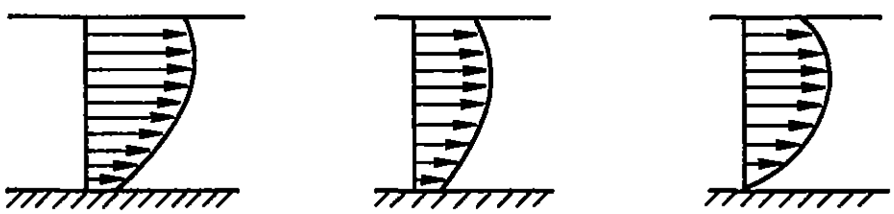
Both velocity and the concentration of suspended solids in storm sewers vary with position in the sewer cross-section. The manner in which velocity is distributed in the sewer section seriously affects those flow measurement methods which require independent determination of average velocity. Some typical velocity profiles are shown in Figure 2. With open-channel flow, higher velocities are usually found near the surface and lower velocities near the bottom. Average velocity in the vertical is at about 0.6 depth. Velocities are higher near the center of the pipe or conduit than near the outer boundaries. When the conduit is surcharged and is flowing full, lines of equal velocity tend to be concentric, with the higher velocity near the center. On horizontal curves, higher velocities are on the outside of the curve due to the centrifugal inertia force. Because the effect of curvature on flow often continues downstream for a considerable distance, a normal distribution of velocity is not found on a curve, or downstream for a distance of several sewer widths.

Suspended solids heavier than water have their lowest concentration near the surface, and the concentration increases with depth. A "bed load", composed almost entirely of heavier solids, may occur near the bottom of the sewer. This may "slide" along the bottom or, with insufficient flow velocity, may rest on the bottom. As the velocity and turbulence increase, the "bed load" may be picked up and suspended in the sewage. At the beginning of storm runoff, as water picks up solids which have accumulated in the sewer upstream during periods of no rainfall, the flow may be composed largely of sewage solids, or bed load, which appears to be pushed ahead by the water.

Suspended materials lighter than water, such as oils and grease, float on the surface - as do leaves, limbs, boards, and some cloth and paper materials. Other small, light particles are moved randomly within the flow by turbulence. Larger, heavier suspended and floating solids tend to move to the outside of a horizontal curve, following the stream lines of higher velocity.



a) FULL PIPE FLOWING UNDER PRESSURE



b) SOME OPEN CHANNEL FLOW PROFILES

Figure 2. Typical Vertical Velocity Profiles

Combined Sewer Flows

Combined sewers are designed to carry both stormwater and sanitary sewage and/or industrial wastes. Therefore, except for their sanitary and industrial sewage components (dry-weather flow), they have the same flow characteristics as storm sewers. As indicated earlier, where municipal ordinances are lax or not enforced with respect to sanitary or industrial sewer connections to them, storm sewers are little different from combined sewers. As combined sewers are designed, dry-weather flow generally includes only a small portion of the total sewer flow. However, due to overloading in many rapidly developing areas, the dry-weather flow sometimes requires a much larger percentage of total capacity. Furthermore, stormwater runoff usually increases dramatically with urbanization.

Because the design, or available, capacity of combined sewers for carrying stormwater is probably less than is usually provided in storm sewers, they either become surcharged more frequently, or the excess flow is diverted to overflow lines.

NEED FOR FLOW MEASUREMENT

Measurements of quantity of flow, usually in conjunction with sampling for flow quality, are essential to nearly all aspects of water pollution control. Research, planning, design, operation and maintenance, and enforcement of pertinent laws - all are activities which rely on flow measurement for their effective conduct. For some activities, very precise, time synchronized, continuous flow records are needed. With others, occasional, fairly rough estimates of flow may suffice.

Research

A principal research activity is the development of an extensive backlog of data to characterize the various types of wastewater - e.g., sanitary and industrial wastes, stormwater, combined sewage, and effluents from treatment plants. The quantity and rate of sanitary sewage flow from individual homes, apartments, and commercial buildings, as found in various cities and geographic locations, provide data useful for many purposes. Similarly, measurement of the flow of wastes from specific industrial processes provides general information concerning the character of such industrial wastes. Characterization of stormwater and combined sewage with respect to geographic location, population density, land use, and other parameters, makes reasonably accurate estimation for unmeasured areas possible. Similarly, flow records from a network of natural streams throughout the country, such as those maintained by the U.S. Geological Survey, make possible the characterization of ungaged streams which may be required to receive wastewaters.

Mathematical models of the relationships between rainfall, runoff, basin characteristics, and concentration of pollutants in the runoff, such as the Storm Water Management Model of the USEPA, are being developed. The principal limiting factor in the development and testing of such models has been the scarcity of satisfactory data on the quantity and quality of runoff in urban areas. Although these models can perform a very useful function in synthesizing flow records, they do not fully substitute for actual flow measurements and records. For example, application of a model to an unfamiliar area needs verification by actual records, and adjustments to the model are often indicated.

Planning

The availability of reasonably accurate and long-term records of flow is a basic requirement for planning new or expanded systems of sewers, or systems for the control and/or treatment of stormwater and combined sewage. Such records, with records of water quality, are required to define the scope of the problem to be solved, and to make necessary decisions concerning the type, size, number, and location of facilities required.

A knowledge of existing flow conditions, plus knowledge of existing pollutant concentrations, is indicative of conditions to be expected in the future, and thus serves to define the problem. For example, infiltration into sewers is a common problem which must be addressed to avoid excessive construction and operational costs. Flow measurements can serve to locate the approximate source and quantity of such infiltration.

For storm and combined sewer systems, knowledge of the number, frequency, and pollutant loadings (the product of quantity and concentration) of overflows is necessary to evaluate their impact on the receiving stream. Thus, the extent and seriousness of the problem can be determined.

In many cases, the sources and movement of stormwater pollutants are not obvious. They may originate partly through rain and snowfall over a city; from the surfaces of buildings, streets, vacant land, construction sites, parking lots, and yards in urban runoff; and in the sewer system. Often the sources and movements of such pollutants can be determined through a systematic program of flow measurement and sampling, thus outlining the necessary extent of a pollution control system or program.

A significant number of procedures and facility types are available to management for the control of pollution due to stormwater and combined sewage. In general, these include methods for controlling the quantity of flow, and those for treating, or improving the quality, of wastewater.

Quantity of stormwater can be controlled at the source by increasing infiltration to groundwater, and can be controlled in the sewer system itself by reducing infiltration to the system, by using the maximum capacity of the system itself for storage, and by other procedures. Facilities for temporary storage of wastewater outside of the sewer system can be provided.

A number of physical, chemical, combinations of physical-chemical, and biological methods have been considered in the Storm and Combined Sewer Pollution Control Program of the USEPA for treatment of stormwater and combined sewage. In most cases, some type of control such as reduction of instantaneous peak flows is essential for practical application of treatment methods. Selection of suitable facilities and procedures for control of peak flows depends upon the availability of storm hydrograph records.

Character of storm runoff as influenced by geographic differences in storm patterns, intensity, and frequency is defined by records of flow and is the basis for decision on the type of pollution control system to be used. As stated by Lager and Smith (5), "*Storms of high intensity and short duration may be best countered with storage, whereas storms of low intensity and long duration may be more effectively controlled through increased treatment capacity or runoff deterrents such as porous pavements. Intervals between storms are significant in that they may dictate dewatering requirements and, in turn, treatment rates in system cleanup from one storm in preparation for the next.*"

Design

Design of facilities for temporary storage of wastewater within the sewer system - such as flow control structures, and off-line storage facilities - must be based largely on records of peak flows and storm hydrographs. Such data are often most useful when converted to figures of frequency of peak flows or of runoff volume-duration-frequency. The probability of a second storm occurring within a selected time interval is also useful in sizing storage facilities. It should be recognized that wastewater pollution control facilities can, in most cases, be designed to handle runoff only from storms of comparatively short recurrence intervals. Runoff from larger storms, of relatively infrequent recurrence intervals, may completely submerge the facility and surrounding area, and the only design concern would be protection from damage.

If, for example, screens are to be used for treatment, the number and size of units, size of screen openings, and other design characteristics (such as frequency of screen cleaning) must depend largely on the rate and volume of wastewater flow to be handled and on the concentration of pollutants. Similarly, if chemical treatment is to be used, the number and size of units, the quantity of chemicals, and the design of equipment for chemical handling must be based on records of peak flow and volume of flow, as modified by storage.

Operation and Maintenance

Although operational guides and maintenance procedures are often based on historical records of flow, flow records obtained on a "real-time" basis may be more useful for operational purposes. Where temporary storage within an extensive system of sewers is controlled by computer, flows at remote locations may be sensed and telemetered to the computer. The system can thus be regulated to more fully utilize its total capacity. If temporary offline storage is to be utilized within a combined sewer system, a preselected rate of flow, or stage, in the sewer could serve to initiate diversion to storage. Efficient operation of systems for wastewater pollution control must depend upon measurement and sampling of flows. In fact, operation of the large-scale, high-rate systems that may often be required for control and treatment of stormwater and combined sewage will not be possible without coordinated systems of flow measurement and sampling.

Permits and Enforcement

Section 402 of the Federal Water Pollution Control Act Amendments of 1972 (6), "...*creates a National Pollutant Discharge Elimination System under which the Administrator of the Environmental Protection Agency may, after opportunity for public hearings, issue permits for the discharge of any pollutant or combination of pollutants, upon condition that such discharge will meet all applicable requirements of the Act relating to effluent limitations, water quality standards and implementation plans, new source performance standards, inspection, monitoring and entry provisions, and guidelines establishing ocean discharge criteria.*"

The Act requires that the Administrator of the USEPA prepare, and make public, a fact sheet for every permit application having a total discharge volume of more than 500,000 gallons on any day of the year. (The Administrator may prepare fact sheets for smaller discharges.) Included in the fact sheet must be: "*A quantitative description of the discharge described in the NPDES application which includes the rate or frequency of the proposed discharge; if the discharge is continuous, the average daily flow in gallons per day or million gallons per day;*"

Provision is made for enforcement of the Act by recourse to criminal, civil, and civil injunctive remedies. Thus, measurement of flow is one of the basic requirements for issuance of a permit to discharge pollutants.

TYPES OF FLOW DATA REQUIRED

Basic flow data can be classified in accordance with their probable accuracy, time continuity or discontinuity, and their general quantity level - such as high, medium, or low. All flow data must be synchronized with time, at least on a watch time basis, to have any useful meaning. For some purposes, such as certain research or operation functions, very precise time synchronization is necessary. To increase their usefulness, various statistical parameters such as totals, means, extremes, variability, and frequency are derived by analysis of the basic flow data.

Continuous records of flow for the time period of interest probably are most commonly required. For planning and design of pollution control facilities, or for determining the effects of pollution on the receiving stream, many years of continuous record of flow may be useful. Continuous "real-time" data for operation of facilities may be needed for an indefinite time period.

In many storm sewers, flow outside the periods of storm runoff is negligible. Therefore, the need is for continuous record of flow during periods of storm runoff only. Flow measurement equipment can be activated automatically by the onset of rainfall, or by preselected water surface elevation, and can be deactivated in a similar manner.

There may be situations where the magnitude and frequency of peak flows only would be required. These data could, for example, be required for determination of the maximum required size of sewers or other facilities. In this case, crest-stage measurements only can be obtained by various simple devices such as a vertical pipe stilling well with a graduated rod left in it. Maximum stage is recorded by a line of ground cork, or other floatable material, left on the stick during a period of storm runoff. A calibrated primary device, such as a culvert, flume, or rated channel, must be used with the crest-stage measuring equipment.

On the other hand, measurements of low flow only can be useful. This would be true in cases where low flow augmentation of the receiving stream could be an acceptable measure for reducing the concentration of pollutants in the stream. Because of the usual slow change in streamflow during periods of dry weather, comparatively few measurements are needed to define such low flows.

Another type of flow measurement, often known as a miscellaneous measurement, is made only at rather infrequent intervals of time. The time interval may be regular, or it may be simply at the convenience of the hydrographer. Such measurements are useful where flow is known to be relatively steady. Flows of effluent from treatment plants, effluent from selected types of industrial plants, sanitary sewage, or storm sewers during periods of dry weather may be satisfactorily defined by miscellaneous measurements.

Often, flow measurements are made for the purpose of calibrating another, possibly continuous type, flow measurement device. For example, a series of current meter measurements may be made over a range of stages to calibrate a measuring flume which may not be precalibrated satisfactorily.

The probable accuracy of flow data is determined by a number of factors. Each type of flow measurement equipment has an inherent maximum capability for accuracy. Care with which certain types of equipment are installed affects the accuracy of the flow data. Conditions under which the equipment is used influence the accuracy of the data collected. The harsh conditions found in many sewers can be detrimental to measuring equipment, and makes the work of the hydrographer difficult. Use of certain types of equipment necessitates considerable training and experience if accurate records are to result. Estimates of probable accuracy of the data should always be furnished by field personnel as a guide to the user, who otherwise has little means of knowing if they should be rated as excellent, good, fair, or poor.

SECTION IV

THE TIME ELEMENT IN FLOW DATA

Measurements of flow are useful only with respect to the relationship of the measured flow with other phenomena. An assignment of time of occurrence to flow data makes possible a determination of its relationship to other parameters whose times of occurrence are known. The other parameters of interest may or may not be synchronous with the flow data. In some cases, definition of the time interval between events is sufficient but, generally, the true clock time, preferably standard time, of the concerned flow is required.

IMPORTANCE OF THE TIME ELEMENT

The required accuracy of the time element in flow data is very different from requirement to requirement. An example is the use of peak flows for each year to determine their frequency. On the other hand, flows at intervals as short as one minute have been collected to define the discharge hydrograph from small urban areas.

A particular need for improved accuracy in the time element occurs in the measurement of flows from small urban storm sewers in order to define the hydrograph and to provide data for development and verification of rainfall-runoff-quality models. Accurate definition of both the time and discharge elements of the hydrograph makes possible the computation of total volume of runoff during the storm by computing the area under the hydrograph, exclusive of base flow. By selecting a number of well defined hydrographs resulting from storms of similar rainfall characteristics, a typical hydrograph for the basin can be defined. When the hydrograph is so adjusted that its runoff volume is 2.54 cm (1.00 in.) of rainfall excess, it is called a "unit hydrograph", and it can be conveniently used to define hydrographs resulting from similar rainfalls of any volume of rainfall excess. Shape of the unit hydrograph is determined by accurate timing as well as by discharge, although it is independent of clock time. The hydrograph as defined by clock time and discharge is often used to route flows along a stream channel or through a reservoir.

Peak flows, storm runoff volumes, daily flows, or other flow parameters are often correlated with similar flows at other points on a storm sewer or stream, or with flows of other storm sewers or streams, to provide a means for flow estimation. Also, correlations may be made with various physical characteristics of a basin, such as area, slope, population density, etc. Correlations with temperature, soil moisture, or antecedent precipitation may be made at times. In most cases, it is essential that the correlated variables be synchronous, so accurate timing of the data is often required.

Timing of measured flows and collection of quality samples can be useful in determining sources of pollution. For example, they can be related to time of release of pollutants from industrial plants, or to the time of accidental spills of pollutants. The time of travel of pollutants along a stream or storm sewer can be estimated from the time of travel of small rises or other flow changes in the channel.

In many situations where flow measurement is used for operation of pollution control facilities, accurate timing of the flows may be required. This is particularly true where upstream flow data are transmitted electronically for automatic control of gates, pumps, and other devices for the relief of stormwater flows.

CONTINUOUS RECORDING OF FLOWS

Many different kinds of equipment are available for the continuous recording of flow data. In general, they consist of a clock, or timer, which drives or regulates the rate of motion of a strip chart or tape, or a circular chart. Discharge may be recorded directly on the chart by pen, pencil, or digital punch; or, stage only may be recorded for later conversion to discharge by means of known relationships of stage to discharge. This conversion may be made manually, with the aid of a discharge integrator, or by means of a computer where digital punched tape is available.

Adjustments, or corrections, to the record are usually required. The clocks or timers in general use do not maintain fully accurate chart time. Sliding time corrections are made for the periods between visits when the chart position of the pen is compared with watch time of the hydrographer. Small errors in discharge or stage are similarly corrected for the periods between visits. Careful review of the charts may reveal periods of clock stoppage, temporary backwater conditions, or instrument malfunctions for which corrections may be made.

When the relationship between stage and discharge is nonlinear, rapidly changing stages must be subdivided into relatively short periods before converting to discharge. Due to intermittent use of daylight saving time, and inconsistent use of such time from place to place, all flow records should be adjusted to standard time.

Clock Drives and Timers

Clock drives commonly used on flow recorders include spring wound, suspended weight, battery powered motor, and synchronous motor (alternating current). Except for those driven by synchronous motor through a power system of regulated frequency, significant time errors can be expected. Errors of one or two hours per week are common with recorders of the 8-day type. Without careful clock adjustment, errors of several hours per month in continuous-type recorders are to be expected. Timers on the digital paper punches now widely used in the field by the U.S. Geological Survey are said to provide correct timing within about 15 minutes per month. Where required, more accurate timers are available to substitute for those in more general use. Extremely accurate time can be maintained with quartz crystal timers, for example. The cost of such solid state timers is not high, except for those having refinements such as compensation for error due to temperature change.

Synchronous data recording is often achieved by the tracing of more than one data parameter on a single chart controlled by a single timer. Thus, flow data may be traced together with rainfall data to provide a better relationship between rainfall and runoff. On one existing project, flow data from several sites are being transmitted to a central location and traced on a single chart. Although the data thus recorded are synchronous, they are not necessarily plotted to correct clock time. In several systems of combined sewers, "real-time" rainfall, quality, and flow data are transmitted to a central computer, which analyzes the data to provide control of gates, pumps, and regulators for optimum system operation.

Recorder Charts and Tapes

Difficulty in recording the correct time of flow data arises not only from error of timers, but also from mechanical inaccuracies in the recorders, and from nonconstant dimensions of the recorder paper. Under moist, humid conditions, most paper charts expand a significant amount. Expansion of more than 0.5 percent is to be expected at times. Error due to expansion of a strip chart could thus be one hour (or more) in 10 days of operation. A recorder with an auxiliary pen that marks the paper at uniform intervals of clock time, rather than relying upon preprinted time divisions on the chart, serves as a basis for correction due to humidity effects.

Timing of digital paper tape punch recorders is not affected by changes in the paper tape length because the punches occur at uniform intervals of clock time.

NONCONTINUOUS FLOW DATA

Other flow measurements, such as the miscellaneous type, are usually made directly by the hydrographer and are timed by his watch. It is important that he maintain his watch as accurately as possible, and that he note the time as standard or daylight saving, whichever it may be.

It is neither possible, nor necessary, to determine the precise time for crest-stage measurements of peak flows obtained as described above. Usually, the time can be established closely enough for the purpose by comparison with the corresponding peak stage at a nearby flow recording site.

SECTION V

DESIRABLE EQUIPMENT CHARACTERISTICS

From the brief review of the severe conditions and vagaries of storm and combined sewer flow and discussions given in the preceding sections, it is intuitively obvious that a number of very stringent design requirements must be placed on flow measurement devices if they are to function satisfactorily in such an application. It should also be apparent that no single design can be considered ideal for all flow measurement activities in all storm and combined sewer flows of interest. Characteristics of the available sites, as well as the particular flows in question, make a device that might be acceptable for one location totally unsuitable for another. Despite this, one can set forth some equipment "requirements" in the form of primary design goals and some desirable equipment features in the form of secondary design goals.

PRIMARY DESIGN GOALS

The following are considered to be primary design goals for equipment that is to be used to measure storm and combined sewer flows:

Range - Since flow velocities may range from 0.03 to 9 meters per second (0.1 to 30 fps), it is desirable that the unit have either a very wide range of operation; be able to automatically shift scales; or otherwise cover at least a 100 to 1 range.

Accuracy - For most purposes, an accuracy of ±10% of the reading at the readout point is necessary, and there will be many applications where an accuracy of ±5% is highly desirable. Repeatability of better than ±2% is desired in almost all instances.

Flow Effects on Accuracy - The unit should be capable of maintaining its accuracy when exposed to rapid changes in flow; e.g., depth and velocity changes in an open channel flow situation. There are instances where the flows of interest may accelerate from minimum to maximum in as short a time period as five minutes.

Gravity and Pressurized Flow Operation - Because of the conditions that exist at many measuring sites, it is very desirable that the unit have the capability (within a closed conduit) of measuring over the full range of open channel flow as well as with the conduit flowing full and under pressure.

Sensitivity to Submergence or Backwater Effects - Because of the possibility of changes in flow resistance downstream of the measuring site due to blockages, rising river stages including possible reverse flow, etc., it is highly advantageous that the unit be able to continue to function under such conditions or, at a minimum, be able to sense the existence of such conditions which would lead to erroneous readings.

Effect of Solids Movement - The unit should not be seriously affected by the movement of solids such as sand, gravel, debris, etc. within the fluid flow.

Flow Obstruction - The unit should be as nonintrusive as possible to avoid obstruction or other interference with the flow which could lead to flow blockage or physical damage to some portion of the device.

Head Loss - To be usable at a maximum number of measurement sites, the unit should induce as little head loss as possible.

Manhole Operation - To allow maximum flexibility in utilization, the unit should have the capability of being installed in confined and moisture-laden spaces such as sewer manholes.

Power Requirements - The unit should require minimum power at the measuring site to operate; the ability to operate on batteries is a definite asset for many installations.

SECONDARY DESIGN GOALS

The following are desirable features for flow measuring equipment, especially for use in a storm or combined sewer application:

Site Requirements - Unit design should be such as to minimize site requirements, such as the need for a fresh water supply, a vertical drop, excessive physical space, etc.

Installation Restrictions or Limitations - The unit should impose a minimum of restrictions or limitations on its installation and be capable of use on or within sewers of varying size.

Simplicity and Reliability - To maximize reliability of results and operation, the design of the unit should be as simple as possible, with a minimum of moving parts, etc.

Unattended Operation - For the majority of applications, it is highly desirable that the equipment be capable of unattended operation.

Maintenance Requirements - The design of the equipment should be such that routine maintenance is minimal and troubleshooting and repair can be effected with relative ease, even in the field.

Adverse Ambient Effects - The unit should be unaffected by adverse ambient conditions such as high humidity, freezing temperatures, hydrogen sulphide or corrosive gases, etc.

Submersion Proof - The unit should be capable of withstanding total immersion without significant damage.

Ruggedness - The unit should be of rugged construction and as vandal and theft proof as possible.

Self Contained - The unit should be self contained insofar as possible in view of the physical principles involved.

Precalibration - In order to maximize the flexibility of using the equipment in different settings it is desirable that it be capable of precalibration; i.e., it should not be necessary to calibrate the system at each location and for each application.

Ease of Calibration - Calibration of the unit should be a simple, straightforward process requiring a minimum amount of time and ancillary equipment.

Maintenance of Calibration - The unit should operate accurately for extended periods of time without requiring recalibration.

Adaptability - The system should be capable of: indicating and recording instantaneous flow rates and totalized flows; providing flow signals to associated equipment (e.g., an automatic sampler); implementation of remote sensing techniques or incorporation into a computerized urban data system, including a multisensor single readout capability.

Cost - The unit should be affordable both in terms of acquisition and installation costs as well as operating costs, including repair and maintenance.

EVALUATION PARAMETERS

It is, of course, not necessary that all of the primary and secondary design goals be achieved for all flow measurement requirements. For example, "spot" measurements of all flow rather than continuous records are sufficient at times. Flow measurement devices used to calibrate others need not necessarily be self contained, nor would unattended operations be required. Furthermore, meeting all of the listed design goals for all installations and settings would be difficult, if not impossible, to achieve in a single design.

Nonetheless, the primary and secondary design goals can be used to formulate a set of evaluation parameters against which a given design or piece of equipment can be judged. Since application details may make certain parameters more or less important in one instance or another, no attempt has been made to apply weighting factors or assign numerical rank. It is hoped that the evaluation factors will prove useful, as a check list among other things, for the potential user who has a flow measurement requirement and who may require assistance in the selection of his equipment.

The evaluation parameters, together with qualitative scales, are presented in the form of a flow measurement equipment checklist in Table 1.

TABLE 1. FLOW MEASUREMENT EQUIPMENT CHECKLIST

Designation: ____

	Evaluation Parameter	Scale			Weight and Score
1	Range	☐ Poor	☐ Fair	☐ Good	
2	Accuracy	☐ Poor	☐ Fair	☐ Good	
3	Flow Effects on Accuracy	☐ High	☐ Moderate	☐ Slight	
4	Gravity & Pressurized Flow Operation	☐ No		☐ Yes	
5	Submergence or Backwater Effects	☐ High	☐ Moderate	☐ Low	
6	Effect of Solids Movement	☐ High	☐ Moderate	☐ Slight	
7	Flow Obstruction	☐ High	☐ Moderate	☐ Slight	
8	Head Loss	☐ High	☐ Medium	☐ Low	
9	Manhole Operation	☐ Poor	☐ Fair	☐ Good	
10	Power Requirements	☐ High	☐ Medium	☐ Low	
11	Site Requirements	☐ High	☐ Moderate	☐ Slight	
12	Installation Restrictions or Limitations	☐ High	☐ Moderate	☐ Slight	
13	Simplicity and Reliability	☐ Poor	☐ Fair	☐ Good	
14	Unattended Operation	☐ No		☐ Yes	
15	Maintenance Requirements	☐ High	☐ Medium	☐ Low	
16	Adverse Ambient Effects	☐ High	☐ Moderate	☐ Slight	
17	Submersion Proof	☐ No		☐ Yes	
18	Ruggedness	☐ Poor	☐ Fair	☐ Good	
19	Self Contained	☐ No		☐ Yes	
20	Precalibration	☐ No		☐ Yes	
21	Ease of Calibration	☐ Poor	☐ Fair	☐ Good	
22	Maintenance of Calibration	☐ Poor	☐ Fair	☐ Good	
23	Adaptability	☐ Poor	☐ Fair	☐ Good	
24	Cost	☐ High	☐ Medium	☐ Low	
25	Portability	☐ No		☐ Yes	

Comments:

SECTION VI

METHODS OF FLOW DETERMINATION

GENERAL

This section is intended to provide the reader with an overview of the physical principles that have been utilized in the design of equipment for the quantitative measurement of flows. It presents a discussion, in generic terms, that may help the reader to better follow the treatment of commercially available equipment given in Section VII. There are a number of excellent references on the subject and the reader is referred to them for a more in-depth presentation. Noteworthy among these are the ASME monograph on fluid meters (7) which was used as a guide for the organization of this section as well as much of its content, Replogle (8) and McMahon (9) which were also liberally used as resource material; the USDI Bureau of Reclamation's water measurement manual (10), the Leupold and Stevens water resources data book (11), and the many standard texts on hydraulics, fluid mechanics, etc.

Any flow measurement system can be considered to consist of two distinct parts, each of which has a separate function to perform. The first, or primary element, is that part of the system which is in contact with the fluid, resulting in some type of interaction. The secondary element is that part of the system which translates this interaction into the desired readout or recording. While there is almost an endless variety of secondary elements, primary elements are related to a more limited number of physical principles, being dependent upon some property of the fluid other than, or in addition to, its volume or mass such as kinetic energy, inertia, specific heat, or the like. Thus the primary elements, or rather their physical principles, form a natural classification system for flow measuring devices and are so used in this discussion.

Flow measurement systems may be thought of as belonging to one of two rather broad divisions, quantity and rate. In quantity meters, the primary element measures isolated (i.e., separately counted) quantities of fluid either in terms of mass or volume. Usually a container or cavity of known capacity is alternately filled and emptied, permitting an essentially continuous flow of the metered supply. The secondary element counts the number of these quantities and indicates or records them, often against time. In rate meters, by contrast, the fluid passes in a continuous, uninterrupted stream, which interacts with the primary element in a certain way, the interaction being dependent upon one or more physical properties of the fluid. In the secondary element, the quantity of flow per unit time is derived from this interaction by known physical laws supplemented by empirical relations. A general categorization of flow meters by division, classification, type, and sub-type is presented in Table 2. Each classification is discussed briefly in the following sub-sections.

A slightly modified form of the flow measurement equipment checklist given in Table 1 has been used to evaluate the various flow measuring devices and techniques in tabular form, and a matrix summary is given at the end of this section. It must be re-emphasized that these evaluations are made with a storm or combined sewer flow measurement application in mind and will not necessarily be applicable for other types of flows. They are necessarily somewhat subjective, and the writers apologize in advance to the clever reader who has made a particular device work satisfactorily in such an application and, hence, feels that it has been treated unfairly.

Only a few of the evaluation parameters normally have numbers associated with them. To assist the reader in interpreting the ratings, the following general guidelines were used. If the normal range of a particular device was considered to be less than about 10:1, it was termed poor; if it was considered to be greater than around 100:1, it was termed good. The intermediate ranges were termed fair. The accuracy that might reasonably by anticipated in measuring storm or combined sewer flows was considered rather than the best accuracy achievable by a particular device. For example, although a sharp-crested weir may be capable of achieving accuracies of ±1.5% or better in clear irrigation water flows, accuracies of much better than ±4-7% should not necessarily be anticipated for a sharp-crested weir measuring stormwater or combined sewer discharges. If the accuracy of a particular flow measuring device or method was considered to be better than around ±1-2%, it was termed good; if it was considered to be worse than around ±10%, it was termed poor. The intermediate accuracies were termed fair.

The flow measuring devices and techniques were not rated on two evaluation parameters, submersion proof and adaptability, because these factors are so dependent upon the design details of the secondary element selected by the user.

SITE SELECTION

The success or failure of selected flow measurement equipment or methods, with respect to accuracy and completeness of data collected as well as reasonableness of cost, depends very much on the care and effort execised in selecting the gaging site. Except for a few basic requirements which are applicable to all types of equipment and methods which will be discussed at this point, there are significant differences in site needs for various flow measurement devices. Particular site requirements will be addressed in the discussion of each equipment type.

A requirement which appears to be obvious, but which is frequently not sufficiently considered, is that the site selected be located to give the desired flow measurement. Does flow at the site provide information

TABLE 2. FLOW METER CATEGORIZATION

DIVISION	CLASSIFICATION	TYPE	SUBTYPE
QUANTITY	GRAVIMETRIC	WEIGHER	
QUANTITY	GRAVIMETRIC	TILTING TRAP	
QUANTITY	GRAVIMETRIC	WEIGH DUMP	
QUANTITY	VOLUMETRIC	METERING TANK	
QUANTITY	VOLUMETRIC	RECIPROCATING PISTON	
QUANTITY	VOLUMETRIC	OSCILLATING OR RING PISTON	
QUANTITY	VOLUMETRIC	NUTATING DISC	
QUANTITY	VOLUMETRIC	SLIDING VANE	
QUANTITY	VOLUMETRIC	ROTATING VANE	
QUANTITY	VOLUMETRIC	GEAR OR LOBED IMPELLER	
QUANTITY	VOLUMETRIC	DETHRIDGE WHEEL	
RATE	DIFFERENTIAL PRESSURE	VENTURI	
RATE	DIFFERENTIAL PRESSURE	DALL TUBE	
RATE	DIFFERENTIAL PRESSURE	FLOW NOZZLE	
RATE	DIFFERENTIAL PRESSURE	ROUNDED EDGE ORIFICE	
RATE	DIFFERENTIAL PRESSURE	SQUARE EDGE ORIFICE	CONCENTRIC
RATE	DIFFERENTIAL PRESSURE	SQUARE EDGE ORIFICE	ECCENTRIC
RATE	DIFFERENTIAL PRESSURE	SQUARE EDGE ORIFICE	SEGMENTED
RATE	DIFFERENTIAL PRESSURE	SQUARE EDGE ORIFICE	GATE OR VARIABLE AREA
RATE	DIFFERENTIAL PRESSURE	CENTRIFUGAL	ELBOW OR LONG RADIUS BEND
RATE	DIFFERENTIAL PRESSURE	CENTRIFUGAL	TURBINE SCROLL CASE
RATE	DIFFERENTIAL PRESSURE	CENTRIFUGAL	GUIDE VANE SPEED RING
RATE	DIFFERENTIAL PRESSURE	IMPACT TUBE	PITOT-STATIC
RATE	DIFFERENTIAL PRESSURE	IMPACT TUBE	PITOT VENTURI
RATE	DIFFERENTIAL PRESSURE	LINEAR RESISTANCE	PIPE SECTION
RATE	DIFFERENTIAL PRESSURE	LINEAR RESISTANCE	CAPILLARY TUBE
RATE	DIFFERENTIAL PRESSURE	LINEAR RESISTANCE	POROUS PLUG
RATE	VARIABLE AREA	GATE	
RATE	VARIABLE AREA	CONE AND FLOAT	
RATE	VARIABLE AREA	SLOTTED CYLINDER AND PISTON	
RATE	HEAD-AREA	WEIR	SHARP CRESTED
RATE	HEAD-AREA	WEIR	BROAD CRESTED
RATE	HEAD-AREA	FLUME	VENTURI
RATE	HEAD-AREA	FLUME	PARSHALL
RATE	HEAD-AREA	FLUME	PALMER-BOWLUS
RATE	HEAD-AREA	FLUME	DISKIN DEVICE
RATE	HEAD-AREA	FLUME	CUTTHROAT
RATE	HEAD-AREA	FLUME	SAN DIMAS
RATE	HEAD-AREA	FLUME	TRAPEZOIDAL
RATE	HEAD-AREA	FLUME	TYPE HS, H, AND HL
RATE	HEAD-AREA	OPEN FLOW NOZZLE	
RATE	FLOW VELOCITY	FLOAT	SIMPLE
RATE	FLOW VELOCITY	FLOAT	INTEGRATING
RATE	FLOW VELOCITY	TRACER	
RATE	FLOW VELOCITY	VORTEX	VORTEX-VELOCITY
RATE	FLOW VELOCITY	VORTEX	EDDY-SHEDDING
RATE	FLOW VELOCITY	TURBINE	
RATE	FLOW VELOCITY	ROTATING ELEMENT	HORIZONTAL AXIS
RATE	FLOW VELOCITY	ROTATING ELEMENT	VERTICAL AXIS
RATE	FORCE-DISPLACEMENT	VANE	
RATE	FORCE-DISPLACEMENT	HYDROMETRIC PENDULUM	
RATE	FORCE-DISPLACEMENT	TARGET	
RATE	FORCE-DISPLACEMENT	JET DEFLECTION	
RATE	FORCE-DISPLACEMENT	BALL AND TUBE	
RATF	FORCE-MOMENTUM	AXIAL FLOW MASS	
RATE	FORCE-MOMENTUM	RADIAL MASS	
RATE	FORCE-MOMENTUM	GYROSCOPIC	
RATE	FORCE-MOMENTUM	MANGUS EFFECT	
RATE	THERMAL	HOT TIP	
RATE	THERMAL	COLD TIP	
RATE	THERMAL	BOUNDARY LAYER	
RATE	OTHER	ELECTROMAGNETIC	
RATE	OTHER	ACOUSTIC	
RATE	OTHER	DOPPLER	
RATE	OTHER	OPTICAL	
RATE	OTHER	DILUTION	
RATE	OTHER	ELECTROSTATIC	
RATE	OTHER	NUCLEAR RESONANCE	

actually needed to fulfill project needs? Sometimes influent flows, diversions, or storage upstream or downstream from the selected site would bias the data in a manner not understood without a thorough study of the proposed site. Such study would include reference to surface maps and to sewerage maps and plans. Sometimes groundwater infiltration or unrecorded connections may exist. For these reasons, a thorough field investigation should be made before establishing a flow measurement site.

There are some situations where there is no choice of sites. Only a single site may be available where the desired flow measurement can be made. In this case, the problem is one of selecting the most suitable flow measurement equipment and methods for the available site.

A basic consideration in site selection is the possible availability of flow measurements or records collected by others. At times, data being collected by the U.S. Geological Survey, by the State, or by other public agencies can be used. There are locations where useful data, although not currently being collected, may have been collected in prior years. Additional data to supplement those earlier records may be more useful than new data collected at a different site. Other general site considerations include any history of surcharging, entry and backwater conditions, and intrusion from receiving waters.

Requirements which apply to all flow measurement sites are accessibility, personnel and equipment safety, and freedom from vandalism. If a car or other vehicle can be driven directly to the site at all times, the cost in time required for installation, operation, and maintenance of the equipment will be less, and it is possible that less expensive equipment can be selected. Consideration should be given to access during periods of adverse weather conditions and during periods of flood stage. Sites on bridges or at manholes where heavy traffic occurs should be avoided unless suitable protection for men and equipment is provided. If entry to sewers is required, the more shallow locations should be selected where possible. Manhole steps and other facilities for sewer access must be carefully inspected, and any needed repairs made. Possible danger from harmful gases, chemicals, or explosion should be investigated. With respect to sites at or near streams, historical flood marks should be determined and used for placement of access facilities and measurement equipment above flood level where this is possible. Areas of known frequent vandalism should be avoided.

Selection of sites in open, rather than secluded, areas may help to reduce vandalism. Often, the only solution to prevent destruction of facilities is to place them in solid concrete or steel shelters, and to surround them with heavy fencing. Erection of warning signs is futile, as they often serve only to provide targets.

In development of a system or network of flow measurement stations, primary consideration must be given to cost if the maximum benefit is to result from available funds. Therefore, cost must be considered in selection of each gaging site. Cost reduction can result from selection of sites where the less expensive types of equipment, which will fulfill project requirements of accuracy and completeness, can be installed. For example, if a site is selected where conditions are such that satisfactory records can be obtained with a weir installation, this would be preferable to selecting a site where the head loss required by a weir would not be available, and the expense of installing a Parshall flume must be met.

GRAVIMETRIC

As indicated in Table 2, gravimetric meters include weighers, tilting trap and weigh dump meters. Weighing the fluid is a primary standard and, since the accuracy of weighing devices is routinely considered to be better than ±0.1%, they are frequently used to calibrate other meters as, for example, at the new National Bureau of Standards flowmeter calibration facility. In its simplest form, a gravimetric meter involves determining the weight of a quantity of fluid in a tank mounted on beam scales, load cells, or some other mass or force measuring device. Where flow is uniform, an indication of flow rate can be obtained by measuring the time over which the measured weight of fluid is gathered. The tipping bucket rain gage is probably one of the most common meters of this type in field use. Another field application, used where a scale or some other weighing device is available, is the simple "bucket and stopwatch" technique. Practical considerations limit the use of this technique to fairly low flow rates, however. Gravimetric meters may often have a useful range of up to 100:1, and accuracies of ±1% of the reading or better are routine.

All types of gravimetric meters as a class are evaluated in Table 3. Since they are generally not well suited for storm or combined sewer flow measurement, no further discussion will be given.

VOLUMETRIC

Whenever the fluid density can be assumed to be reasonably constant, a volumetric measure of flow is adequate. Because of their simplicity and lower cost as compared to gravimetric meters, most quantity meters found on the market today are volumetric devices. A representative, but not inclusive, listing of types of volumetric meters is given in Table 2. As with gravimetric devices, rates of flow can be indicated with many volumetric meters by using appropriate secondary elements.

Probably the most elementary type of volumetric device is the metering tank. An open tank is repeatedly filled to a fixed depth and emptied.

TABLE 3. GRAVIMETRIC METER EVALUATION (ALL TYPES)

	Evaluation Parameter	Scale		
1	Range	☐ Poor	☐ Fair	☒ Good
2	Accuracy	☐ Poor	☐ Fair	☒ Good
3	Flow Effects on Accuracy	☒ High	☐ Moderate	☐ Slight
4	Gravity & Pressurized Flow Operation	☐ No		☒ Yes
5	Submergence or Backwater Effects	☐ High	☐ Moderate	☒ Low
6	Effect of Solids Movement	☒ High	☐ Moderate	☐ Slight
7	Flow Obstruction	☒ High	☐ Moderate	☐ Slight
8	Head Loss	☒ High	☐ Medium	☐ Low
9	Manhole Operation	☒ Poor	☐ Fair	☐ Good
10	Power Requirements	☐ High	☒ Medium	☐ Low
11	Site Requirements	☒ High	☐ Moderate	☐ Slight
12	Installation Restrictions or Limitations	☒ High	☐ Moderate	☐ Slight
13	Simplicity and Reliability	☒ Poor	☐ Fair	☐ Good
14	Unattended Operation	☐ No		☒ Yes
15	Maintenance Requirements	☒ High	☐ Medium	☐ Low
16	Adverse Ambient Effects	☐ High	☒ Moderate	☐ Slight
17	Submersion Proof	☐ No		☐ Yes
18	Ruggedness	☐ Poor	☒ Fair	☐ Good
19	Self Contained	☐ No		☒ Yes
20	Precalibration	☐ No		☒ Yes
21	Ease of Calibration	☐ Poor	☐ Fair	☒ Good
22	Maintenance of Calibration	☐ Poor	☒ Fair	☐ Good
23	Adaptability	☐ Poor	☐ Fair	☐ Good
24	Cost	☒ High	☐ Medium	☐ Low
25	Portability	☒ No		☐ Yes

Although potentially not as accurate as weighing, since both the fluid and tank are subject to temperature effects, accuracies of about ±1% of reading are routinely achieved. The usable range of a metering tank device is a function of its design, but 10:1 is commonly achieved.

There have been a few instances where existing structures have been used as volumetric flow measuring devices for stormwater or combined sewage. For example, in at least one location wet wells have been utilized in a "fill and draw" fashion in order to provide an indication of flow. The monitoring of pump operations at lift stations in general has been used in a number of cases to obtain flow information. Such techniques rely upon the use of existing equipment and structures, however, and flow measurement was not their original purpose. For this reason, they must be considered as techniques of opportunity rather than as candidates for flow measurement equipment per se; consequently, they will not be included in the evaluation table.

Many of the flow measuring devices in the volumetric classification are positive displacement meters. Such units may be considered to be fluid motors operating with a very high volumetric efficiency under a very light load. This load is made up of two parts; the internal load due to friction within the primary element, and the external load imposed by the secondary element or register. As in all fluid motors, work done against a load results in a pressure drop. The main factors influencing the magnitude of this pressure drop are the type of seal required, the power required to drive the register, the viscosity of the liquid, and the rate of flow.

Various ingenious mechanical implementations of such meters include such types as the reciprocating piston, oscillating or ring piston, nutating disc, sliding and rotating vane, and gear or lobed impeller. Several of these have seen application in water meter designs for residential and commercial use. They are seldom found in large sizes and are obviously poorly suited for measuring storm or combined sewer flows. A special adaptation of a vane type meter is the Dethridge Wheel. These devices are widely used in Australia and New Zealand to measure irrigation water flows, but are almost unknown in the United States. Accuracies of ±3.5% are reported for free discharge conditions for discharge rates between 0.042 and 0.14 cm/s (1.5 and 5.0 cfs). Maximum ranges of 5:1 have been achieved in smaller sizes.

All types of volumetric meters as a class are evaluated in Table 4. Since they are generally not well suited for storm or combined sewer flow measurement, no further discussion will be given. Complete descriptions and discussions can be found in the references - especially ASME (7), Replogle (8), and McMahon (9).

TABLE 4. VOLUMETRIC METER EVALUATION (ALL TYPES)

	Evaluation Parameter	Scale		
1	Range	☒ Poor	☐ Fair	☐ Good
2	Accuracy	☐ Poor	☐ Fair	☒ Good
3	Flow Effects on Accuracy	☒ High	☐ Moderate	☐ Slight
4	Gravity & Pressurized Flow Operation	☐ No		☒ Yes
5	Submergence or Backwater Effects	☐ High	☐ Moderate	☒ Low
6	Effect of Solids Movement	☒ High	☐ Moderate	☐ Slight
7	Flow Obstruction	☒ High	☐ Moderate	☐ Slight
8	Head Loss	☐ High	☒ Medium	☐ Low
9	Manhole Operation	☒ Poor	☐ Fair	☐ Good
10	Power Requirements	☐ High	☐ Medium	☒ Low
11	Site Requirements	☒ High	☐ Moderate	☐ Slight
12	Installation Restrictions or Limitations	☒ High	☐ Moderate	☐ Slight
13	Simplicity and Reliability	☐ Poor	☒ Fair	☐ Good
14	Unattended Operation	☐ No		☒ Yes
15	Maintenance Requirements	☒ High	☐ Medium	☐ Low
16	Adverse Ambient Effects	☐ High	☒ Moderate	☐ Slight
17	Submersion Proof	☐ No		☐ Yes
18	Ruggedness	☐ Poor	☒ Fair	☐ Good
19	Self Contained	☐ No		☒ Yes
20	Precalibration	☐ No		☒ Yes
21	Ease of Calibration	☐ Poor	☐ Fair	☒ Good
22	Maintenance of Calibration	☐ Poor	☒ Fair	☐ Good
23	Adaptability	☐ Poor	☐ Fair	☐ Good
24	Cost	☒ High	☐ Medium	☐ Low
25	Portability	☒ No		☐ Yes

DIFFERENTIAL PRESSURE

Flow measuring devices that fall in the differential pressure classification operate by converting energy from one form to another. For example, in those primary devices that have a reduced cross-section, potential energy is converted into kinetic energy to produce a differential pressure, while in the impact type devices the reverse is true. Centrifugal type devices utilize the acceleration of the flow around a bend, while linear resistance type devices are based on frictional losses. In many designs a combination of velocity head, frictional losses, or stream-line bending is employed. An important feature of all flow measuring devices in the differential pressure classification used here is that they can only be used in a closed conduit flowing full and under pressure.

Venturi

As noted above, when a fluid flows through a conduit of varying cross-section its velocity varies from point to point along the conduit or passage. If the velocity increases, the passage is called a nozzle, and the kinetic energy increases at the expense of internal energy. If the velocity decreases, the passage is called a diffuser, and the internal energy increases at the expense of kinetic energy. If the cross-section of a nozzle decreases continuously from entrance to exit it is called converging, and if it increases continuously it is called diverging. The cross-section of a diffuser may either increase or decrease depending on whether the flow is supersonic or subsonic. A venturi is a converging nozzle followed by a subsonic diffuser. The region of minimum cross-section is called the throat. A number of different venturi geometries have been developed over the years, one of the more common being the standard (long-type) Herschel Venturi meter tube (Figure 3).

The venturi meter is one of the most accurate devices for measuring liquid flow rates in pipes, but it is not in common use for waste flow measurement for a number of reasons, not the least of which is its cost. The venturi causes a very low pressure loss and, with proper precautions, is good for use in liquids with high solids concentrations. For example, ASTM Standard D 2458 states (12) "*When a venturi tube is to be used for metering liquids containing large concentrations of suspended solids or sludge, the annular ring is eliminated and replaced by single hole taps at the inlet and throat and these are flushed continuously with clean water.*" It is further recommended that the flushing water pressure should exceed the maximum line pressure by at least 0.7 kgf/sq cm (10 psi). The flushing water flows should be equal and continuous, and held to a small quantity to prevent any measurable pressure differential which would be reflected in the metering instrument.

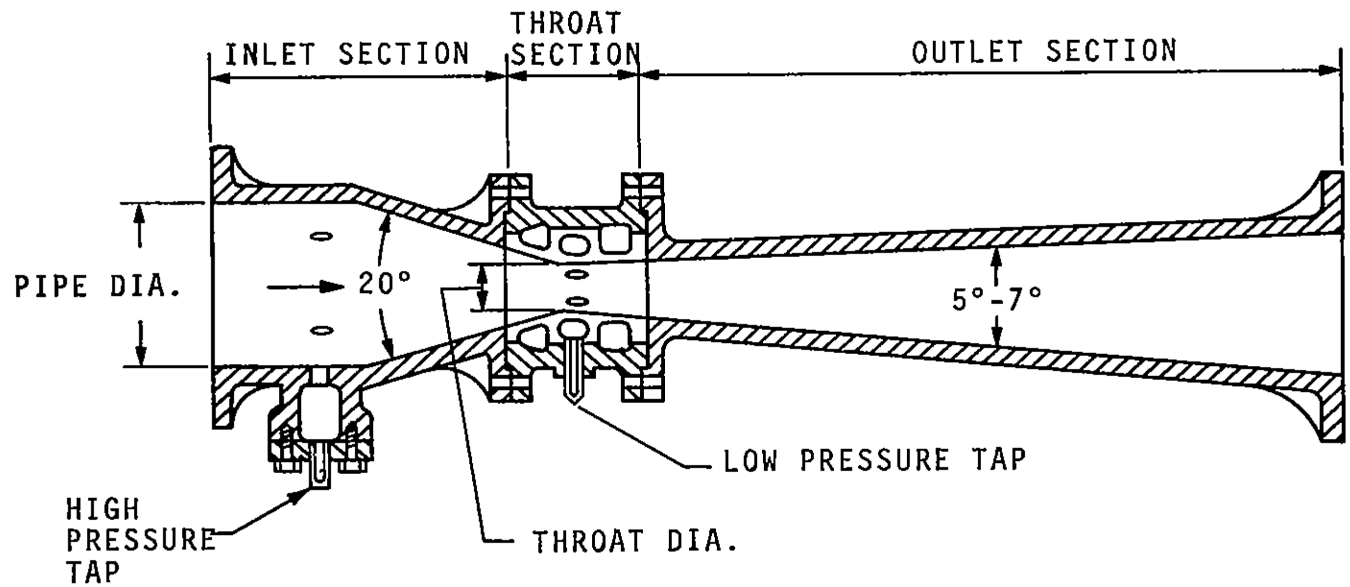


Figure 3. Herschel Standard (Long) Venturi Meter Tube

It is essential that the flow entering a venturi tube be of uniform turbulence, free from helical flow and from high or low pressure areas. Therefore, long uninterrupted runs of straight pipe upstream from the venturi location are desirable for accurate fluid metering. Straightening vanes can often be used to reduce the upstream straight pipe run requirement when the disturbing device produces spiral flows, but they do little to reduce the effects of elbows and partly opened gate valves. The required run depends upon the nature of the upstream element; e.g., elbow, gate and globe valve, decreaser, increaser, etc., and the ratio of the throat diameter to the pipe diameter. Typically, the minimum desirable straight run will be from 5 to 20 pipe diameters. Conditions downstream from the venturi tube have little effect on its performance.

The pressure differential of a venturi tube can be measured using mercury columns, electrically, pneumatically, or by incorporating a water level sensing device (e.g., a float operated instrument) and water columns. Although manufacturers typically supply rating curves with their instruments, ASTM (12) recommends that each venturi be calibrated in place to meet accuracy standards. Accuracy is affected by changes in density, temperature, pressure, viscosity, and by pulsating flow. Under ideal conditions a venturi can yield accuracies of around ±0.5% of the reading, but more typical accuracies achieved are about ±1 or 2%. Most installations are usable over a range of 5:1 or so. Venturi tube meters are evaluated in Table 5.

Flow Tubes

Following the development of the Herschel venturi tube in 1887, a number of variations such as the short-coned venturi were developed. Among the more recently introduced venturi-type primary devices is the Dall flow tube (13), which was developed in England. The Dall tube consists of a flanged cylindrical body designed with a short straight inlet section which terminates abruptly with a decrease in diameter, thus forming a shoulder. This is followed by a conical reducer and diverging outlet separated by a narrow throat. In effect, the Dall tube uses stream-line bending as well as velocity head to obtain a differential pressure larger than that produced by a standard venturi meter. Single hole pressure taps are located at the inlet shoulder and the throat (Figure 4). Both pressure taps can be continuously flushed with clean water to prevent plugging from solids in the flow as done with the venturi tube.

The Dall tube is almost as accurate as the standard venturi and has a higher head recovery, being one of the lowest permanent head loss devices known. It is more sensitive to system disturbances than the venturi, and straight upstream pipe runs of 40 pipe diameters or more may be required. Although somewhat cheaper than the venturi, the Dall tube must still be considered expensive. It is much shorter than either

TABLE 5. VENTURI TUBE METER EVALUATION

	Evaluation Parameter	Scale		
1	Range	☒ Poor	☐ Fair	☐ Good
2	Accuracy	☐ Poor	☐ Fair	☒ Good
3	Flow Effects on Accuracy	☐ High	☐ Moderate	☒ Slight
4	Gravity & Pressurized Flow Operation	☒ No		☐ Yes
5	Submergence or Backwater Effects	☐ High	☐ Moderate	☒ Low
6	Effect of Solids Movement	☐ High	☐ Moderate	☒ Slight
7	Flow Obstruction	☐ High	☐ Moderate	☒ Slight
8	Head Loss	☐ High	☐ Medium	☒ Low
9	Manhole Operation	☒ Poor	☐ Fair	☐ Good
10	Power Requirements	☐ High	☐ Medium	☒ Low
11	Site Requirements	☒ High	☐ Moderate	☐ Slight
12	Installation Restrictions or Limitations	☒ High	☐ Moderate	☐ Slight
13	Simplicity and Reliability	☐ Poor	☐ Fair	☒ Good
14	Unattended Operation	☐ No		☒ Yes
15	Maintenance Requirements	☐ High	☒ Medium	☐ Low
16	Adverse Ambient Effects	☐ High	☒ Moderate	☐ Slight
17	Submersion Proof	☐ No		☐ Yes
18	Ruggedness	☐ Poor	☐ Fair	☒ Good
19	Self Contained	☐ No		☒ Yes
20	Precalibration	☐ No		☒ Yes
21	Ease of Calibration	☐ Poor	☐ Fair	☒ Good
22	Maintenance of Calibration	☐ Poor	☐ Fair	☒ Good
23	Adaptability	☐ Poor	☐ Fair	☐ Good
24	Cost	☒ High	☐ Medium	☐ Low
25	Portability	☒ No		☐ Yes

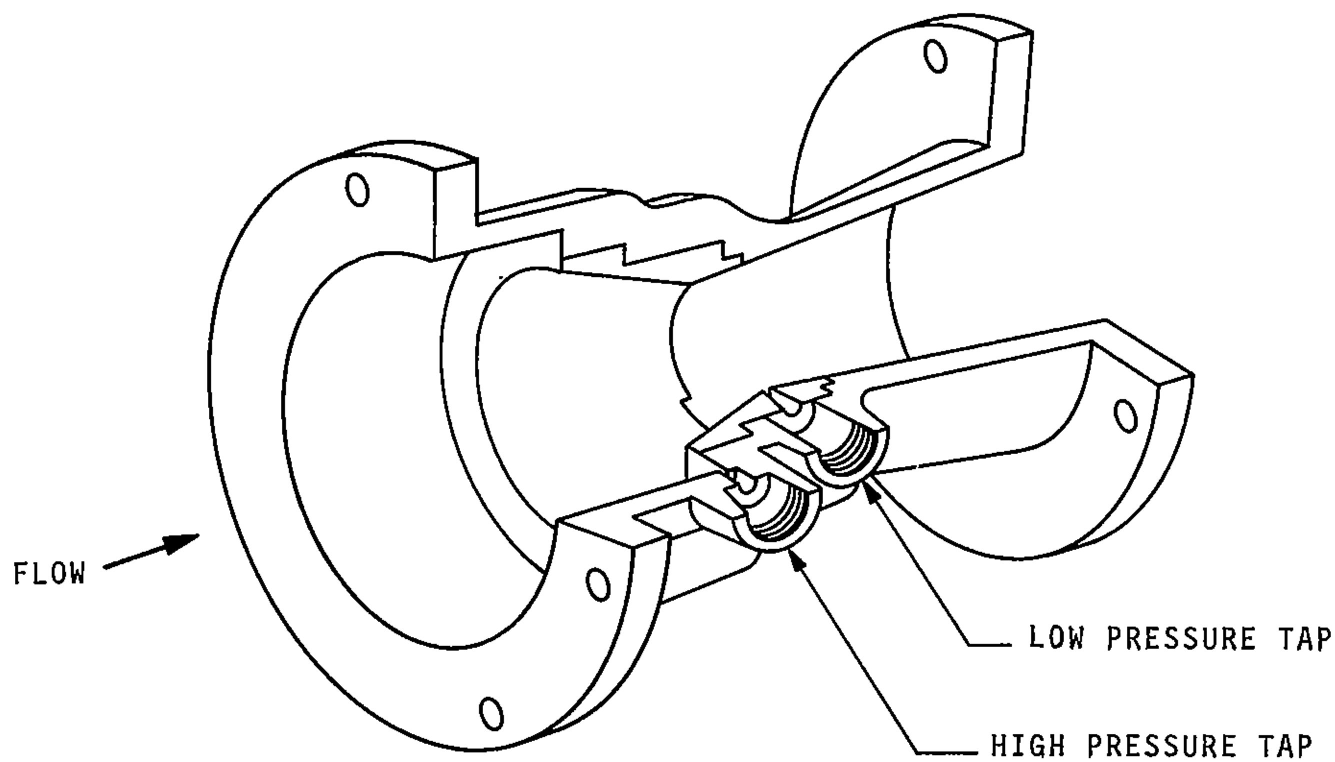


Figure 4. Dall Flow Tube

long or short venturi tubes, and thus has less of an installation restriction. The throat of the Dall tube can foul, and it is not generally recommended for extremely dirty fluids. Dall tubes are evaluated in Table 6.

There have also been a number of recent American proprietary developments, typical of which is the "Lo-Loss" tube. It senses the vacuum at the throat produced by the centrifugal action of the liquid rounding a curve and the impact pressure at the inlet. It is also a high head recovery device but, unlike the Dall tube, can generally be successfully used to meter dirty fluids. With this exception, the evaluation comments of Table 6 can be assumed applicable to the "Lo-Loss" tube also.

The Gentile tube is a somewhat different venturi-type differential pressure producer, in which there is a slight constriction in the line. Pressure ports exist in the wall of the constriction. These ports face in opposite directions and the effect is somewhat similar to the multiple-port Pitot tube. In effect these Pitot tubes are used to amplify the throat pressure. Because of the type of construction and size of the ports, the device has limitations for the measurement of flow of liquids which carry solid matter in suspension. It also suffers from an extremely limited range (less than half that of a Dall tube), a greater sensitivity to upstream disturbances, and less head recovery; consequently, this device will not be discussed further.

Flow Nozzle

Various designs have been developed for flow nozzles, resulting in characteristics that approach those of a venturi tube in one extreme (venturi insert nozzle) and those of an orifice meter in the other (ASME long radius nozzle). More typically, a flow nozzle has an entrance cone and throat, as in a venturi tube, but lacks the recovery cone (diffuser). This omission essentially affects the head recovery only. A major difference (and advantage over the venturi tube) in installation is that a flow nozzle can be installed in pipe flanges (see Figure 5). Nozzles are less expensive than venturi tubes, but cost more than orifice meters. In general they are more sensitive to upstream disturbances and 20 or more pipe diameters of straight run upstream of the flow nozzle are required for successful operation. While some designs, (e.g., ASME nozzle) are quite well suited (with proper precautions) for measuring liquids high in suspended solids, other (e.g., venturi insert nozzle) are not recommended for use in such flows, due to some aspect of their particular design that would tend to promote plugging or clogging. Flow nozzle accuracies can approach those of venturi tubes, especially when calibrated in place. It is also possible to use a flow nozzle in cases where a pipe (flowing full) discharges freely to the atmosphere. In such cases only the high pressure tap is needed; see Figure 6. Flow nozzles as a group are evaluated in Table 7.

TABLE 6. DALL TUBE METER EVALUATION

	Evaluation Parameter	Scale		
1	Range	☒ Poor	☐ Fair	☐ Good
2	Accuracy	☐ Poor	☐ Fair	☒ Good
3	Flow Effects on Accuracy	☐ High	☐ Moderate	☒ Slight
4	Gravity & Pressurized Flow Operation	☒ No		☐ Yes
5	Submergence or Backwater Effects	☐ High	☐ Moderate	☒ Low
6	Effect of Solids Movement	☐ High	☒ Moderate	☐ Slight
7	Flow Obstruction	☐ High	☐ Moderate	☒ Slight
8	Head Loss	☐ High	☐ Medium	☒ Low
9	Manhole Operation	☒ Poor	☐ Fair	☐ Good
10	Power Requirements	☐ High	☐ Medium	☒ Low
11	Site Requirements	☒ High	☐ Moderate	☐ Slight
12	Installation Restrictions or Limitations	☐ High	☒ Moderate	☐ Slight
13	Simplicity and Reliability	☐ Poor	☐ Fair	☒ Good
14	Unattended Operation	☐ No		☒ Yes
15	Maintenance Requirements	☐ High	☒ Medium	☐ Low
16	Adverse Ambient Effects	☐ High	☒ Moderate	☐ Slight
17	Submersion Proof	☐ No		☐ Yes
18	Ruggedness	☐ Poor	☐ Fair	☒ Good
19	Self Contained	☐ No		☒ Yes
20	Precalibration	☐ No		☒ Yes
21	Ease of Calibration	☐ Poor	☐ Fair	☒ Good
22	Maintenance of Calibration	☐ Poor	☒ Fair	☐ Good
23	Adaptability	☐ Poor	☐ Fair	☐ Good
24	Cost	☒ High	☐ Medium	☐ Low
25	Portability	☒ No		☐ Yes

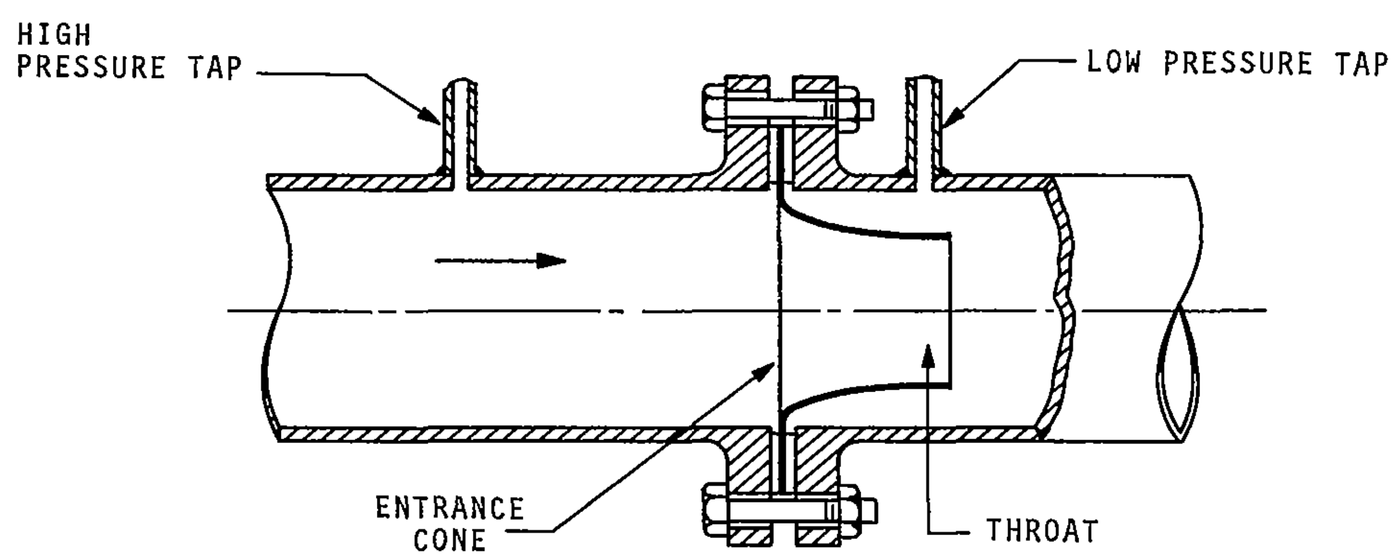


Figure 5. Typical Flow Nozzle Installation

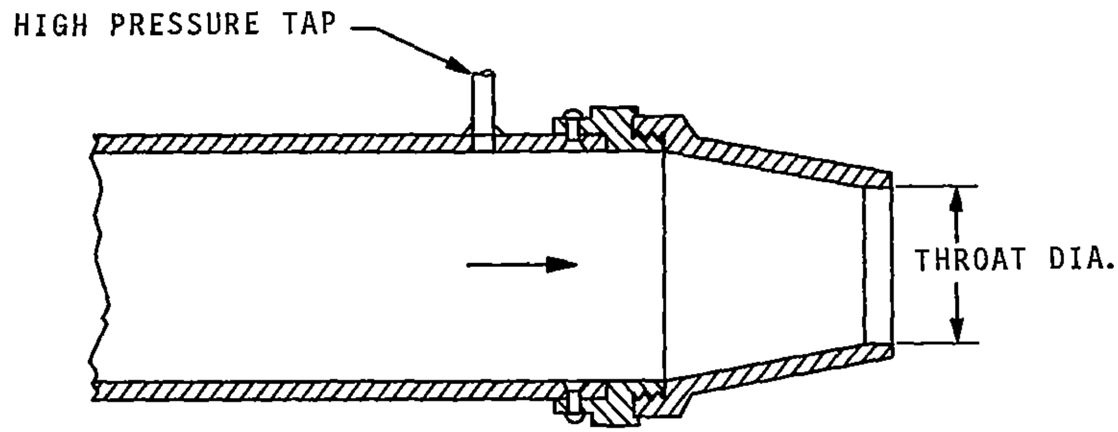


Figure 6. Flow Nozzle Discharging to Atmosphere

TABLE 7. FLOW NOZZLE METER EVALUATION

	Evaluation Parameter	Scale		
1	Range	☒ Poor	☐ Fair	☐ Good
2	Accuracy	☐ Poor	☐ Fair	☒ Good
3	Flow Effects on Accuracy	☐ High	☐ Moderate	☒ Slight
4	Gravity & Pressurized Flow Operation	☒ No		☐ Yes
5	Submergence or Backwater Effects	☐ High	☐ Moderate	☒ Low
6	Effect of Solids Movement	☐ High	☐ Moderate	☒ Slight
7	Flow Obstruction	☐ High	☐ Moderate	☒ Slight
8	Head Loss	☐ High	☒ Medium	☐ Low
9	Manhole Operation	☒ Poor	☐ Fair	☐ Good
10	Power Requirements	☐ High	☐ Medium	☒ Low
11	Site Requirements	☒ High	☐ Moderate	☐ Slight
12	Installation Restrictions or Limitations	☐ High	☒ Moderate	☐ Slight
13	Simplicity and Reliability	☐ Poor	☐ Fair	☒ Good
14	Unattended Operation	☐ No		☒ Yes
15	Maintenance Requirements	☐ High	☐ Medium	☒ Low
16	Adverse Ambient Effects	☐ High	☒ Moderate	☐ Slight
17	Submersion Proof	☐ No		☐ Yes
18	Ruggedness	☐ Poor	☐ Fair	☒ Good
19	Self Contained	☐ No		☒ Yes
20	Precalibration	☐ No		☒ Yes
21	Ease of Calibration	☐ Poor	☐ Fair	☒ Good
22	Maintenance of Calibration	☐ Poor	☐ Fair	☒ Good
23	Adaptability	☐ Poor	☐ Fair	☐ Good
24	Cost	☐ High	☒ Medium	☐ Low
25	Portability	☒ No		☐ Yes

Orifice Meters

The orifice meter is one of the oldest flow measuring devices in existence. Its differential pressure is due to a combination of velocity head, frictional losses, and stream-line bending (acceleration). The relative contribution is determined by whether pipe taps, vena contracta taps, or flange taps are used. The thin plate orifice meter is the most commonly used flow measuring device in pipes. The orifice is a round hole in a thin flat plate that is clamped between a pair of flanges at a point in the pipe. Although some designs have a rounded edge facing into the direction of the flow and perhaps a short tube with the same inside diameter as the orifice diameter extending downstream, it is more common to use a sharp 90-degree corner on the upstream edge. The pressure taps are located upstream and downstream of the orifice plate. An orifice plate can also be used at the end of a pipe flowing full and discharging to atmosphere, in which case only a single pressure tap is required.

Orifice meters work well with clean fluids but are not applicable, except in a limited sense, to flows high in suspended solids due to the tendency of solids to accumulate upstream of the orifice plate and thereby change its calibration. There are two designs that will accommodate limited amounts of suspended solids. The eccentric orifice plate has a hole which is bored off-center, usually tangent to the bottom of the flow line. The segmental orifice plate has a segment removed from the lower half of the orifice plate. In addition, there are many special-purpose devices that are really combinations of flow nozzles and orifice plates. These have arisen due to requirements to minimize viscosity effects in heavy fluids, etc.

Orifice plates are the most sensitive of all the differential pressure devices to effects of upstream disturbances, and it is not uncommon to need 40 to 60 pipe diameters of straight run upstream of the installation. Orifice plates also produce the greatest head loss as can be seen by the comparison curves of Figure 7. Orifice meters can be quite accurate, with ±0.5% or better achievable when calibrated in place. They are lowest in cost of all the differential pressure producers. Because of nonlinear flow effects, their usable range is small (on the order of 5:1) unless rated in place. Orifice meters are evaluated as a group in Table 8.

Centrifugal Meters

Flow acceleration induced in a fluid going around a bend (such as an elbow) produces a differential pressure that can be used to indicate flow. The pressure on the outside of an elbow is greater than on the inside, and pressure taps located mid-way around the bend (i.e., 45 degrees from either flange) can be connected to a suitable secondary

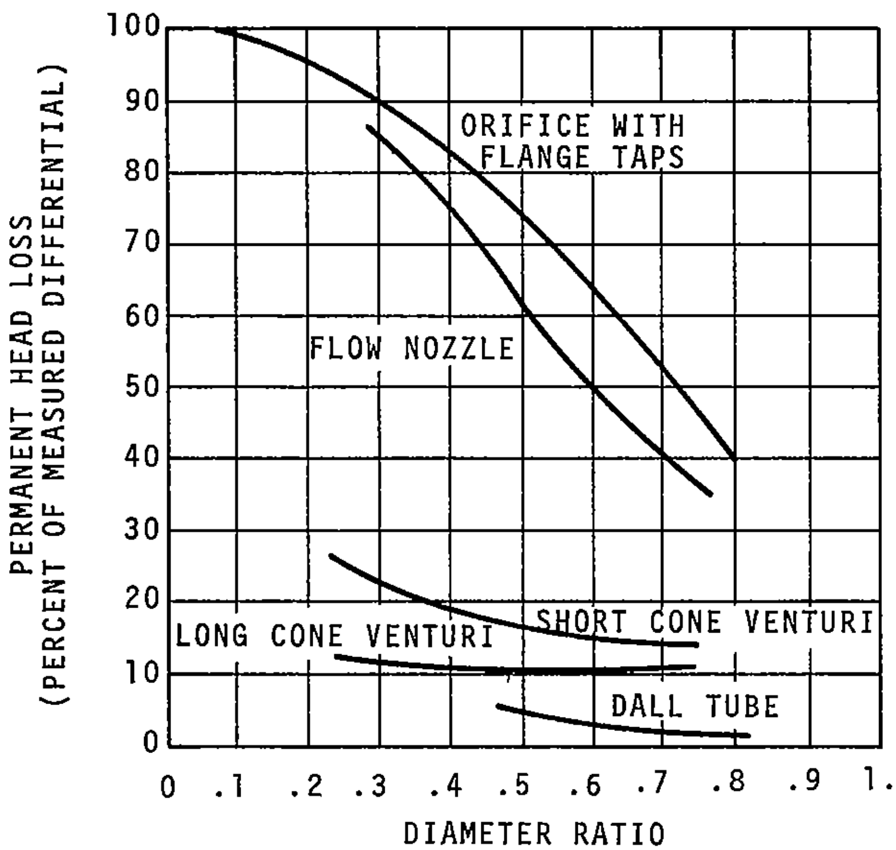


Figure 7. Head Loss of Differential Pressure Meters

TABLE 8. ORIFICE METER EVALUATION

	Evaluation Parameter	Scale		
1	Range	☒ Poor	☐ Fair	☐ Good
2	Accuracy	☐ Poor	☒ Fair	☐ Good
3	Flow Effects on Accuracy	☐ High	☐ Moderate	☒ Slight
4	Gravity & Pressurized Flow Operation	☒ No		☐ Yes
5	Submergence or Backwater Effects	☐ High	☐ Moderate	☒ Low
6	Effect of Solids Movement	☒ High	☐ Moderate	☐ Slight
7	Flow Obstruction	☒ High	☐ Moderate	☐ Slight
8	Head Loss	☒ High	☐ Medium	☐ Low
9	Manhole Operation	☒ Poor	☐ Fair	☐ Good
10	Power Requirements	☐ High	☐ Medium	☒ Low
11	Site Requirements	☒ High	☐ Moderate	☐ Slight
12	Installation Restrictions or Limitations	☐ High	☐ Moderate	☒ Slight
13	Simplicity and Reliability	☐ Poor	☐ Fair	☒ Good
14	Unattended Operation	☐ No		☒ Yes
15	Maintenance Requirements	☒ High	☐ Medium	☐ Low
16	Adverse Ambient Effects	☐ High	☒ Moderate	☐ Slight
17	Submersion Proof	☐ No		☐ Yes
18	Ruggedness	☐ Poor	☒ Fair	☐ Good
19	Self Contained	☐ No		☒ Yes
20	Precalibration	☐ No		☒ Yes
21	Ease of Calibration	☐ Poor	☐ Fair	☒ Good
22	Maintenance of Calibration	☒ Poor	☐ Fair	☐ Good
23	Adaptability	☐ Poor	☐ Fair	☐ Good
24	Cost	☐ High	☐ Medium	☒ Low
25	Portability	☐ No		☒ Yes

element for indicating or recording. Cortelyou (14), Taylor and McPherson (15), and Replogle, et. al. (16) provide fuller discussions of centrifugal meters. The turbine scroll case and guide vane speed ring do not appear at all well suited for storm or combined sewer applications, and so will not be discussed.

The elbow meter may have some application in existing pipe systems. It should not be considered as a candidate for accurate flow measurement in new construction, however. It is inexpensive, offers no additional head loss, can tolerate solids if the pressure taps are flushed (see venturi discussion), and is not especially subject to calibration shifts. If calibrated in place, accuracies of about ±1 or 2% (or better in some cases) may be achieved. More typically, accuracies of 3 to 10% are encountered. Unless calibrated in place, straight pipe runs of at least 20 pipe diameters should be provided both upstream and downstream of the elbow. The usual rangeability is around 3:1. Elbow meters are evaluated in Table 9.

Impact Tube

In the impact tube, kinetic energy (due to fluid velocity) is converted into potential energy (stagnation pressure) and the differential pressure (as compared with static pressure in the pipe) is related to flow velocity at the point of measurement. Figure 8 depicts the two essential ingredients and a particular construction known as the Prandtl-Pitot tube. Alternate designs consist of essentially the same two basic ingredients (impact tube and pressure tube) and differ only in the details of their construction. H. Pitot's original design (1732) had two tubes, one of which was bent through 90 degrees at its lower end and positioned facing into the flow. H. Darcy's design (1852) had each tube bent through 90 degrees, with one facing upstream (impact) and the other facing downstream. In addition to the Prantdl design (with its hemispherical head) which is popular today, especially in Europe, is the Brabbe design with a conical head, which is popular in the United States and United Kingdom. In another design, two parallel small-diameter tubes are beveled at their open ends, one pointing upstream (impact) and one pointing downstream (static).

It must be emphasized that impact tubes measure point velocity only. Flow is calculated by multiplying the mean velocity of the fluid by the area of the pipe cross-section. For pipes flowing full and under pressure it has been determined that the mean velocity of flow is about 83% of the velocity in the center of the pipe and it occurs at a point approximately one-fourth the radius from the wall to the center. Velocity close to the pipe wall is only about one-half the velocity at the center. To avoid upset of such normal velocity distributions it is necessary to have a straight pipe run of some 15 to 50 pipe diameters in length upstream of the measuring point. Alternately, velocity traverses

TABLE 9. ELBOW METER EVALUATION

	Evaluation Parameter	Scale		
1	Range	☒ Poor	☐ Fair	☐ Good
2	Accuracy	☐ Poor	☒ Fair	☐ Good
3	Flow Effects on Accuracy	☐ High	☐ Moderate	☒ Slight
4	Gravity & Pressurized Flow Operation	☒ No		☐ Yes
5	Submergence or Backwater Effects	☐ High	☐ Moderate	☒ Low
6	Effect of Solids Movement	☐ High	☐ Moderate	☒ Slight
7	Flow Obstruction	☐ High	☐ Moderate	☒ Slight
8	Head Loss	☐ High	☐ Medium	☒ Low
9	Manhole Operation	☒ Poor	☐ Fair	☐ Good
10	Power Requirements	☐ High	☐ Medium	☒ Low
11	Site Requirements	☒ High	☐ Moderate	☐ Slight
12	Installation Restrictions or Limitations	☐ High	☐ Moderate	☒ Slight
13	Simplicity and Reliability	☐ Poor	☐ Fair	☒ Good
14	Unattended Operation	☐ No		☒ Yes
15	Maintenance Requirements	☐ High	☐ Medium	☒ Low
16	Adverse Ambient Effects	☐ High	☒ Moderate	☐ Slight
17	Submersion Proof	☐ No		☐ Yes
18	Ruggedness	☐ Poor	☐ Fair	☒ Good
19	Self Contained	☐ No		☒ Yes
20	Precalibration	☒ No		☐ Yes
21	Ease of Calibration	☐ Poor	☒ Fair	☐ Good
22	Maintenance of Calibration	☐ Poor	☐ Fair	☒ Good
23	Adaptability	☐ Poor	☐ Fair	☐ Good
24	Cost	☐ High	☐ Medium	☒ Low
25	Portability	☒ No		☐ Yes

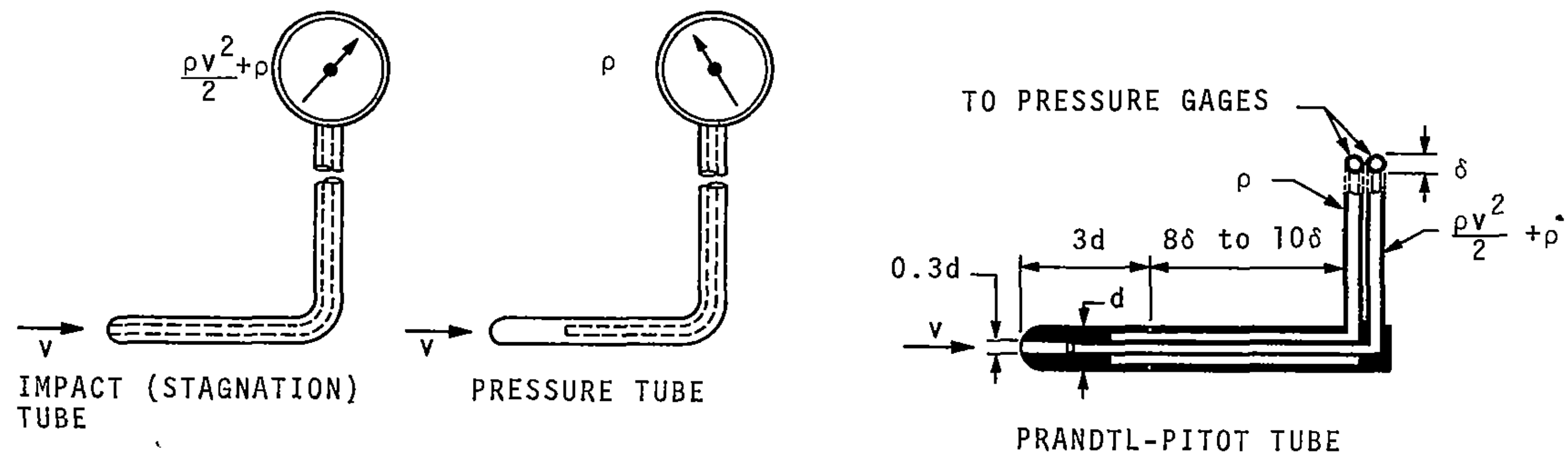


Figure 8. Prandtl-Pitot Impact Tube

can be run to determine the point of mean velocity. Such an approach also allows the pitot tube to be used in conduits of noncircular cross-section and under open channel flow conditions.

With very high velocities dynamic instability may occur, and erroneous readings result from the tube vibrations. However, the chief disadvantage of most pitot tube designs is that rather sophisticated secondary devices are required to accurately determine the pressure differential which may be quite small at low velocities, e.g., less than 0.3 m/s (1 fps). This makes continuous flushing secondary devices more difficult to employ and, to the writers' knowledge, no such attempt has yet been made.

Therefore, impact tube type devices are generally not satisfactory for measuring wastes containing appreciable quantities of suspended solids because of the possibility of plugging of the small openings in the tubes. In view of this, the vulnerability to damage arising from their intrusive nature, and the difficulties in applying them in open channel flows of varying depths, no further discussion will be given.

Linear Resistance

Linear resistance meters use friction losses to create a differential pressure that can be related to flow rate. The resistance of a long pipe section may be used, but one or more fine tubes in parallel (capillary tube) or a section of pipe packed with steel wool, granular materials, or the like (porous plug) are more typical. Fleming and Binder (17), Greef and Hackman (18), and Sovers and Binder (19) discuss various approaches and designs. Accuracies to 1% of the reading and ranges of 10:1 may be achieved. There is no pressure recovery. Because of the impracticality of utilizing such devices for measuring storm or combined sewer flows, they will not be discussed further.

VARIABLE AREA

Whereas differential pressure flow measuring devices are characterized by the invariability of the area ratio, in variable area meters the magnitude of the varying cross-sectional area is the measure of the rate of flow. A differential pressure does exist, but it is relatively constant. Variable area flowmeters may be divided into two main groups, valve type (e.g., hinged or sliding gate) and float type (e.g., cone-and-float). Variable area devices were invented by E. A. Chameroy, who patented an instrument constituting a prototype of the rotameter in 1868, and G. F. Deacon, who was given a patent for a cone-and-disc flowmeter in 1875. Sir J. A. Ewing was the first to apply a tapered glass tube in a liquid rotameter in 1876, and in 1910 K. Kupper introduced inclined slots on the upper rim of the float and first used the term rotameter for this type of device, because of the rotary motion of the float. Discussions of such devices are given by Kehat (20) and Gilmont and Roccanova (21). Accuracies to ±1% of full scale and ranges to 10:1 may be achieved. However, to maintain accuracy in a rotameter it is absolutely essential that both the tube and the float be kept clean. Thus, a storm or combined sewer application would be inappropriate and, consequently, they will not be discussed further.

HEAD - AREA

Flow measurement devices in this classification are characterized by a simultaneous variation of both flow cross-sectional area and head. These parameters do not vary indpendently, however, and it is the function of the primary device to produce a flow that is characterized by a known relationship (usually nonlinear) between a liquid level measurement (head) at some location and the overall discharge. This relationship or head-discharge curve is called the rating for the particular structure or device. Since these devices implicitly require a free surface, they are only suitable for open channel flows.

The change in elevation of the free surface is measured by the secondary device which may also convert stage to discharge automatically. Stilling wells are often used, being connected by suitable taps to the location in the primary device where knowledge of the flow depth is desired. The secondary device then monitors the relatively stable surface level of the fluid in the stilling well. To avoid the necessity of frequent cleaning of the stilling well and to help prevent plugging of the tap, fresh water is frequently trickled into the well at a rate sufficient to ensure that sewage isn't likely to enter. An overpressure of at least 0.003 meter (0.01 ft) is usually required to keep the well and tap clear, but in some cases greater cleaning flows along with frequent flushing will be necessary.

Slope-Area Method

In this technique, the flow conduit itself serves as the primary device. Historically, it has been used to obtain instantaneous discharges rather than continuous records. Some discharge relationship such as the Manning formula is used to relate depth to flow rate. For best results, a straight course of channel of at least 61 meters (200 ft) and preferably up to 305 meters (1000 ft) in length is required. It should be nearly uniform in slope, cross-section, and roughness and free of rapids, abrupt falls (dips), sudden contractions or expansions, and tributary inflows.

The Manning formula requires knowledge of the channel cross-section and liquid depth so that the flow cross-section and hydraulic radius can be calculated. It also requires knowledge of the slope of the water surface (not the conduit invert). This slope may be determined by dividing the difference in the water surface elevations at the two ends of the course, as determined by secondary devices carefully referenced to a common datum level, by the length of the course. Also required in the Manning formula is a roughness factor which depends upon the character of the conduit lining and the depth of flow (i.e., it is not constant for a given channel). Because the proper selection of the roughness factor is at best an estimate, the discharge determined by the slope-area method is only an approximation, and it should be used only where accuracy requirements are low.

All too often, the slope-area method is applied by measuring the flow depth at a single point and using the slope of the conduit invert in the Manning formula. For nonuniform or unsteady flow, the water surface slope will be changing and will certainly not be equal to the channel slope. The Manning formula was not intended for use under such conditions. It is preferable to perform calibration in place and develop an empirical rating curve for each measuring site. The slope-area method is evaluated in Table 10.

Weirs

A weir is essentially an overflow structure or dam built across the flow conduit to measure the rate of flow. For a weir of a given size and shape with free-flow, steady-state conditions and proper weir-to-pool relationships, only one depth of liquid can exist in the upstream pool for a given discharge. Discharge rates are computed by measuring the vertical distance from the crest of the overflow part of the weir to the water surface in the pool upstream of the crest and referring to the rating curve for the particular weir or class of weirs at hand. Thus, a weir may be thought of as a device for shaping the flow of the liquid in a definite way such as to allow a single depth reading to be uniquely related to a discharge rate. Weirs may be further categorized as being either sharp-crested or broad-crested; each will be discussed in turn.

Sharp-Crested Weirs - When the top edge of the weir is thin or beveled with a sharp upstream corner (similar to a thin plate orifice) so that the water does not contact any part of the weir structure downstream but, rather, springs past it, the weir is called a sharp-crested weir. Figure 9 depicts some common weir terms and their relationships. As noted, the minimum height of the weir crest should be at least two, and preferably three, times the maximum head expected over the weir. The contraction of the nappe (overfalling stream) after springing clear of the sharp crest is termed crest contraction. If the bottom of the approach channel is not far enough below the crest of the weir, the crest contraction is partially suppressed, and standard weir tables cannot be used. The slight drop in the liquid surface which begins upstream from the weir a distance of at least twice the head on the crest is called

TABLE 10. SLOPE-AREA METHOD EVALUATION

	Evaluation Parameter	Scale		
1	Range	☐ Poor	☒ Fair	☐ Good
2	Accuracy	☒ Poor	☐ Fair	☐ Good
3	Flow Effects on Accuracy	☒ High	☐ Moderate	☐ Slight
4	Gravity & Pressurized Flow Operation	☒ No		☐ Yes
5	Submergence or Backwater Effects	☒ High	☐ Moderate	☐ Low
6	Effect of Solids Movement	☐ High	☐ Moderate	☒ Slight
7	Flow Obstruction	☐ High	☐ Moderate	☒ Slight
8	Head Loss	☐ High	☐ Medium	☒ Low
9	Manhole Operation	☐ Poor	☐ Fair	☒ Good
10	Power Requirements	☐ High	☐ Medium	☒ Low
11	Site Requirements	☐ High	☒ Moderate	☐ Slight
12	Installation Restrictions or Limitations	☐ High	☐ Moderate	☒ Slight
13	Simplicity and Reliability	☐ Poor	☐ Fair	☒ Good
14	Unattended Operation	☐ No		☒ Yes
15	Maintenance Requirements	☐ High	☐ Medium	☒ Low
16	Adverse Ambient Effects	☐ High	☒ Moderate	☐ Slight
17	Submersion Proof	☐ No		☐ Yes
18	Ruggedness	☐ Poor	☐ Fair	☒ Good
19	Self Contained	☐ No		☒ Yes
20	Precalibration	☒ No		☐ Yes
21	Ease of Calibration	☐ Poor	☒ Fair	☐ Good
22	Maintenance of Calibration	☐ Poor	☐ Fair	☒ Good
23	Adaptability	☐ Poor	☐ Fair	☐ Good
24	Cost	☒ High	☐ Medium	☐ Low
25	Portability	☒ No		☐ Yes

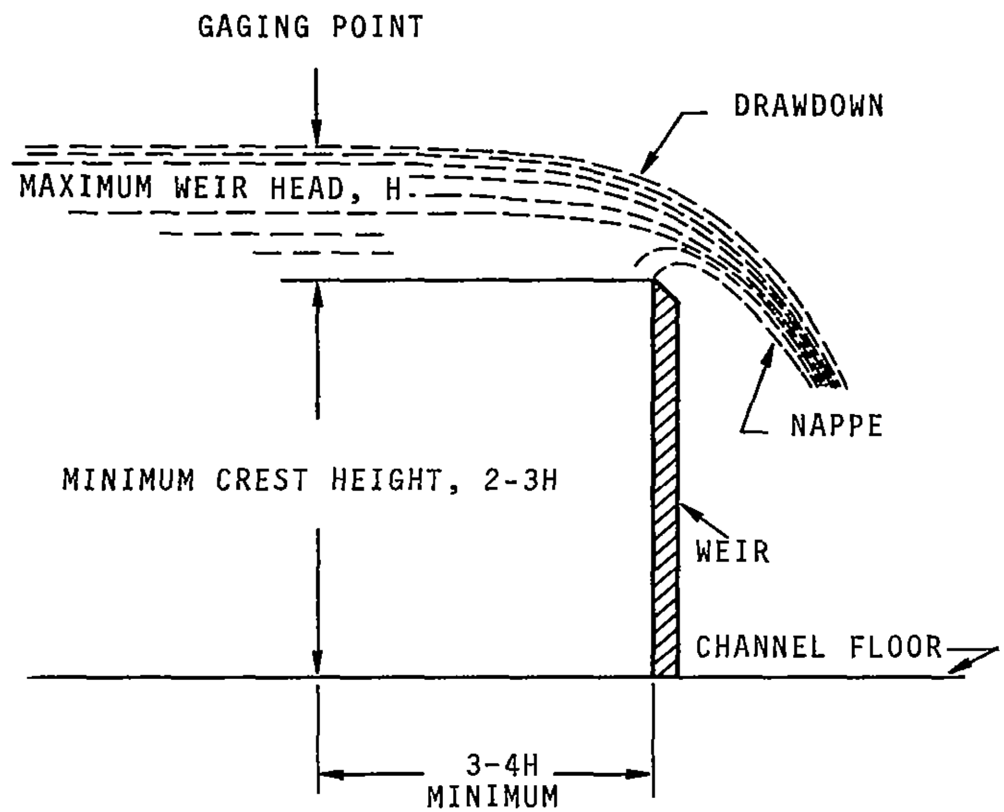


Figure 9. Weir Terms and Their Relationships

surface contraction or drawdown. To avoid sensing the effects of drawdown, the gaging point should be located upstream of the weir crest a distance of at least three, and preferably four, times the maximum head expected over the weir.

When the water level in the downstream channel is sufficiently below the crest to allow free access to the area beneath the nappe, say at least 15 cm (6 in.), the flow is said to be free (critical). When the water level under the nappe rises above the crest elevation, the flow may be considered submerged. This may or may not affect the discharge, and there is some question whether dependable measurements can be expected in this range. As the water level downstream rises appreciably over half of the head on the crest, the degree of submergence will appreciably affect the rate of flow. To determine the rate of flow under such submerged (sub-critical) conditions, both the upstream and downstream heads must be measured and reference made to submerged flow tables. A very good treatment of submerged weirs is given by Skogerboe, et al (22).

Many different geometries have been used for the notch in the weir plate that shapes the nappe and thereby allows the rating curve to be developed. Some sharp-crested weir profiles are depicted in Figure 10.

Rectangular Weirs - One of the oldest and most common is the rectangular weir, which is used in one of two configurations. When the distances from the sides of the weir notch to the sides of the channel (weir pool) are great enough (at least two or three times the head on the crest) to allow the liquid a free, unconstrained lateral approach to the crest, the liquid will flow uniformly and relatively slowly toward the weir sides. As the flow nears the notch it accelerates, and as it turns to pass through the opening, it springs free laterally with a resulting contraction that results in a jet narrower than the weir opening. Under such conditions the weir is called a contracted weir. If a rectangular weir is placed in a channel whose sides also act as the sides of the weir, there can be no lateral contractions and the weir is called a suppressed weir. Special care must be taken with these weirs to assure proper aeration beneath the nappe. This is usually accomplished by placing vents on both sides of the weir box under the nappe.

V-Notch Weirs - The triangular or V-notch sharp-crested weir was developed to allow accurate measurement of small flows. The angle (2α) most commonly used is 90 degrees. Because a V-notch weir has no crest length, the head required for a small flow through it is greater than that required for other common types of weirs. This is an advantage for small discharges in that the nappe will spring free of the crest, whereas it might cling to the crest of another type of profile and make the measurement worthless. The V-notch weir is the best profile for measuring discharges less than 28 ℓ/s (1 cfs) and is as accurate as any

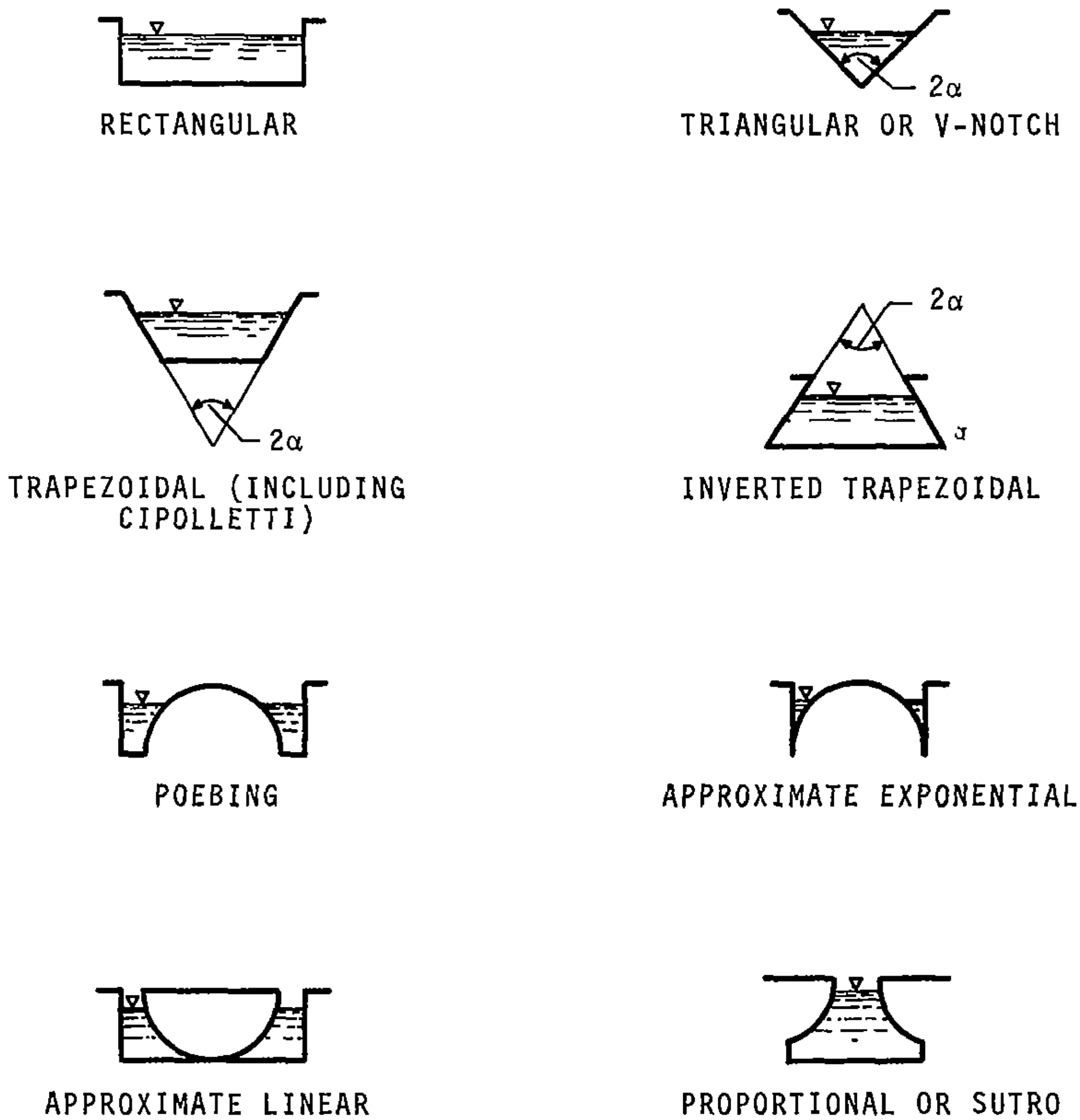


Figure 10. Various Sharp-Crested Weir Profiles

other profile for flows up to 283 ℓ/s (10 cfs). Sufficient head for these higher flow rates may pose a limitation for many sites, however, and in practice 113 ℓ/s (4 cfs) is often a more realistic upper bound.

Trapezoidal Weirs - Trapezoidal weirs of varying side angles have been used to measure liquid flows, but the most common one by far is the Cipolletti, whose sides incline outwardly at a slope of one horizontal to four vertical. Although the Cipolletti weir is a contracted weir, its discharge occurs essentially as though its end contractions were suppressed; thus the width of the crest can be used for flow calculations. It offers a wider range than either the rectangular or V-notch weir.

Other Weirs - Other weir profiles, as indicated in Figure 10, have been developed to achieve certain head-discharge relationships or to achieve some benefit peculiar to a particular type of site. None of these has been used or investigated as extensively as those discussed above, and consequently will not be dealt with here. There is one class of special profiles, however, that at least deserves passing mention. For situations where the normal range of discharges at a site might be easily handled by a V-notch weir but occasional larger flows would require, for example, a rectangular weir, the two profiles have been combined to form what is termed a compound weir, Figure 11.

Such a weir has a disadvantage, however. While flows may be measured rather accurately when the weir is essentially behaving as a V-notch weir, Figure 11a, or as a rectangular (either suppressed or contracted) weir, Figure 11b, there will be a transition zone where accurate readings will be difficult to achieve. When the discharge begins to exceed the capacity of the V-notch, thin sheets of liquid will begin to pass over the wide horizontal crests in a less than predictable fashion. This causes a discontinuity in the discharge curve. The size of the V-notch and the size of the rectangular notch should be selected so that discharge measurements in the transition range will be those of minimum importance.

Discussion - *In order to have a satisfactorily-operating sharp-crested* weir, the following general requirements should be considered:

a. The upstream face of the structure should be smooth and perpendicular to the axis of the channel in both horizontal and vertical directions.

b. The crest should be level, with a sharp right-angled edge on its upstream face; its thickness (in the direction of the flow) should not exceed 3 mm (1/8 in.) and should preferably be between 1 to 2 mm (0.04 to 0.08 in.). Knife edges should be avoided as they are too difficult to maintain.

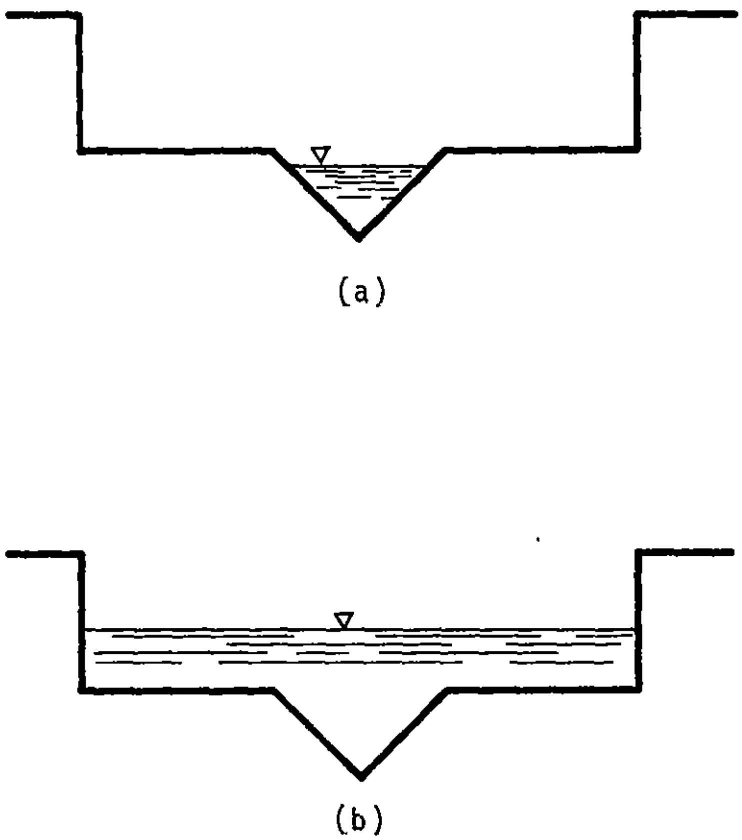


Figure 11. Compound Weir

c. The height of the crest above the approach channel bottom should never be less than 0.3m (1 ft); the minimum head should be at least 0.06m (0.2 ft). For a contracted rectangular weir, the distance from the sides of the weir to the sides of the approach channel should never be less than 0.3m (1 ft).

d. The cross-sectional area of the approach channel should be at least 8 times that of the nappe at the crest for a distance upstream of 15 to 20 times the height on the crest. If the weir pool is smaller than this, the velocity of approach may be too high and the gage readings too low; necessitating head corrections for velocity of approach.

e. The connection between the weir and the channel must be waterproof; i.e., all flow must pass over the weir, not around or under it.

In general, the sharp-crested weir is an inexpensive, accurate primary flow measuring device that is fairly easy to install. Laboratory accuracies approaching 1% of full scale have been achieved, but 5% is more typical of most good field installations. The operating range of a sharp-crested weir depends upon its profile, but 20:1 may be considered typical for many installations. The sharp-crested weir suffers from several deficiencies when considered for a storm or combined sewer application, however. It may well require construction of a weir box to obtain the proper flow approach to the weir. Sufficient head may not be available at the desired measuring site, and the head loss will be at least equal to the head measured. The crest of the weir must be kept clean. Fibers, stringy materials, and larger particles tend to cling to the crest and must be removed periodically.

Finally, because of its damming action, the sharp-crested weir will suffer from settling and accumulation of suspended solids in the approach channel behind the upstream face. This will lead to inaccurate readings. Some weirs have been constructed with a watertight door in the face on the channel bottom. When the door is opened the flow will go through this passage and tend to scour away collected sediment. However, most attempts to use charp-crested weirs in extremely dirty flows have been less than fully successful. Sharp-crested weirs are evaluated as a group in Table 11.

<u>Submerged Orifices</u> - The use of thin-plate orifice meters in pressurized conduit flow has already been discussed. In open channel flow, an orifice operates as a head-area device; in fact, if the water level drops below the top of the opening, it behaves like a weir and has been included here for that reason. Basically, it consists of a predetermined, sharp-edged opening in a plate affixed to a wall or other

TABLE 11. SHARP-CRESTED WEIR EVALUATION (ALL PROFILES)

	Evaluation Parameter	Scale		
1	Range	☐ Poor	☒ Fair	☐ Good
2	Accuracy	☐ Poor	☒ Fair	☐ Good
3	Flow Effects on Accuracy	☐ High	☒ Moderate	☐ Slight
4	Gravity & Pressurized Flow Operation	☒ No		☐ Yes
5	Submergence or Backwater Effects	☐ High	☒ Moderate	☐ Low
6	Effect of Solids Movement	☒ High	☐ Moderate	☐ Slight
7	Flow Obstruction	☒ High	☐ Moderate	☐ Slight
8	Head Loss	☒ High	☐ Medium	☐ Low
9	Manhole Operation	☐ Poor	☒ Fair	☐ Good
10	Power Requirements	☐ High	☐ Medium	☒ Low
11	Site Requirements	☐ High	☒ Moderate	☐ Slight
12	Installation Restrictions or Limitations	☐ High	☒ Moderate	☐ Slight
13	Simplicity and Reliability	☐ Poor	☐ Fair	☒ Good
14	Unattended Operation	☐ No		☒ Yes
15	Maintenance Requirements	☒ High	☐ Medium	☐ Low
16	Adverse Ambient Effects	☐ High	☒ Moderate	☐ Slight
17	Submersion Proof	☐ No		☐ Yes
18	Ruggedness	☐ Poor	☐ Fair	☒ Good
19	Self Contained	☐ No		☒ Yes
20	Precalibration	☐ No		☒ Yes
21	Ease of Calibration	☐ Poor	☐ Fair	☒ Good
22	Maintenance of Calibration	☒ Poor	☐ Fair	☐ Good
23	Adaptability	☐ Poor	☐ Fair	☐ Good
24	Cost	☐ High	☐ Medium	☒ Low
25	Portability	☐ No		☒ Yes

structure and through which flow may occur. Although any shape hole can be used, the most common are either circular or rectangular. Knowledge of the size and shape of the hole, the head acting on it, and the discharge condition (i.e., freely into air or under water) allows determination of the flow rate. Early orifices often discharged freely into air, but were practically abandoned as weirs become more common (and more extensively studied) because of the considerable head loss necessitated by their use.

The fall requirement is reduced if the orifice is lowered in the structure and discharges in the submerged condition. The submerged orifice is used where the head loss of a weir cannot be tolerated and a flume cannot be justified because of cost or some special conditions. Like the weir, a submerged orifice may be either contracted or suppressed. Suppression may occur on part (e.g., the bottom of a rectangular orifice flush with the channel flow) or all of the perimeter.

In selecting a channel site for use of a submerged orifice meter the distance from the edges of the orifice to the bounding surfaces of the channel, both on the upstream and downstream sides, should be greater than twice the least dimension of the orifice if contraction is to be assured. Also, the cross-sectional area of the water prism 6 to 9 m (20 to 30 ft) upstream from the orifice should be at least 8 times the cross-sectional area of the orifice. Velocity of approach to the orifice should be negligible, or correction must be made for velocity head.

An orifice should not be used in situations where weeds and trash are prevalent, as accumulation of submerged debris or of sand and sediment upstream may prevent accurate measurements. A clogged condition of an orifice is less visible than that of a weir and, so, may go undetected. Because of these factors and the small data base as compared to weirs and flumes, an orifice is not generally recommended for measurement of stormwater or combined sewage, even though its limited range of flow can be increased with the use of a metergate, which basically is a modified submerged orifice arranged so that the orifice is adjustable in cross-sectional area. Consequently, no further discussion or evaluation will be given.

Broad-Crested Weirs - If the weir notch is mounted in a wall too thick for the water to spring past, the weir is called broad-crested. A wide variety of shapes can be included under broad-crested weirs, and a wide variety of discharge coefficients will be encountered. A few such shapes are depicted in Figure 12. Broad-crested weirs, in practice, are usually pre-existing structures, such as dams, levees, diversion structures, etc. Discharge coefficients and discharge tables are usually obtained by calibrating the weir in place or by model studies. Broad-crested weirs are sometimes used where the sharp-crested weir causes undue maintenance problems. For example, problems with impact,

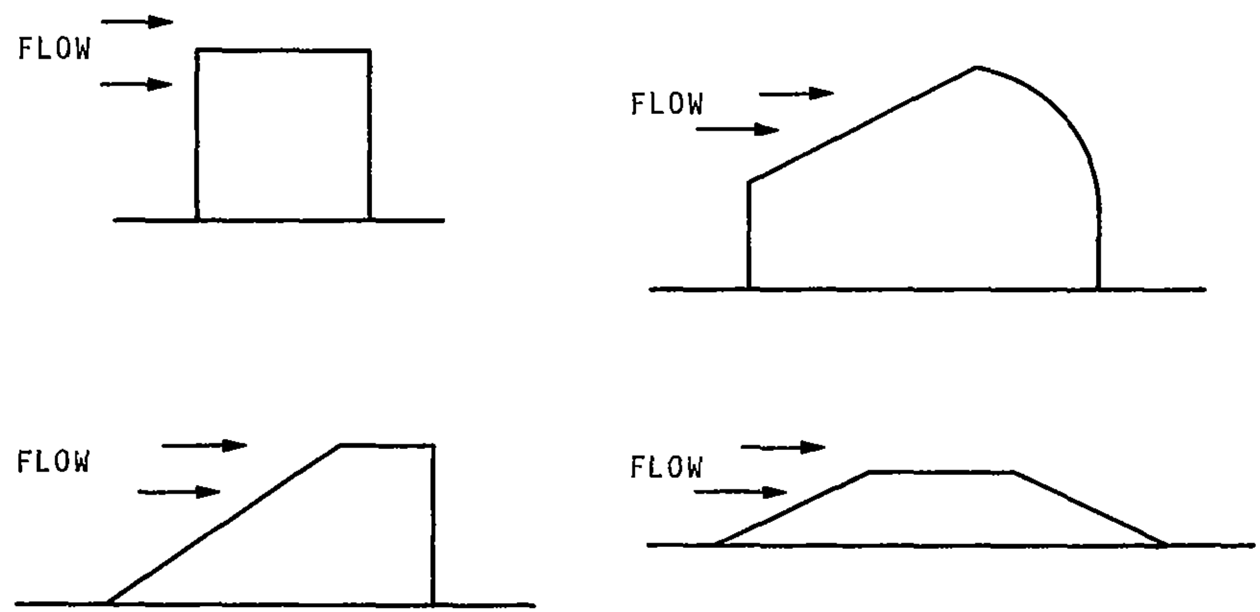


Figure 12. Examples of Broad-Crested Weir Shapes

abrasion, silting, etc. might indicate the need for a broad-crested weir. Broad-crested weirs are usually made of concrete or similar material and are not considered portable. In actuality, the notion of a broad-crested weir, which simply denotes a channel contraction made by a sill on the channel bottom, merges into that of a critical-depth flume. When properly designed and constructed, the broad-crested weir is governed by the same basic flow equations. Broad-crested weirs are evaluated in Table 12.

Flumes

Although the term "broad-crested weir" is widely used to denote a channel constriction made by some sort of a sill on the channel bottom, other open channel constrictions, generally called flumes, have been used to measure discharges since the beginning of the century. Most flumes in common use today can be traced to one of three early design sources: rectangular English flumes based upon early work in India around 1908-1914 and the writings of F. V. A. E. Engal (23); the Parshall flume whose forerunner, a venturi flume developed by Cone (24), was extensively modified and tested by Parshall (25, 26); and flumes of the type first developed by Palmer and Bowlus (27).

Flumes can be categorized as belonging to one of three general families depending upon the state of flow induced - subcritical, critical, or supercritical. By definition the critical flow state is that for which the Froude number is unity. This is the state of flow at which the specific energy is minimum for a given discharge. When critical depth occurs in a channel (either at a constriction or in a regular cross-section), one head measurement can indicate discharge rate if it is made far enough upstream so that the flow depth is not affected by the drawdown of the water surface as it heads to achieve the critical state of flow.

Kilpatrick (28) identifies six approaches employed in various flume designs, and these will be briefly treated below following his discussion.

Type I, tranquil-flow, small-width reduction flumes are typical of the earliest measuring flumes and are depicted in Figure 13. Subcritical flow enters the flume, and the side contractions reduce the width, resulting in an increase in unit discharge. Because there is no change in bed elevation, and minor energy loss, the specific energy in the throat is about the same as in the approach. With constant specific energy, the effect of a small width contraction is a lowering of the water surface in the throat but, owing to the small degree of contraction, critical depth is not accomplished. It is necessary in this type of flume to measure the head in both the approach section and in the throat.

TABLE 12. BROAD-CRESTED WEIR EVALUATION

	Evaluation Parameter	Scale		
1	Range	☐ Poor	☒ Fair	☐ Good
2	Accuracy	☐ Poor	☒ Fair	☐ Good
3	Flow Effects on Accuracy	☐ High	☐ Moderate	☒ Slight
4	Gravity & Pressurized Flow Operation	☒ No		☐ Yes
5	Submergence or Backwater Effects	☒ High	☐ Moderate	☐ Low
6	Effect of Solids Movement	☒ High	☐ Moderate	☐ Slight
7	Flow Obstruction	☐ High	☒ Moderate	☐ Slight
8	Head Loss	☐ High	☒ Medium	☐ Low
9	Manhole Operation	☐ Poor	☐ Fair	☒ Good
10	Power Requirements	☐ High	☐ Medium	☒ Low
11	Site Requirements	☐ High	☒ Moderate	☐ Slight
12	Installation Restrictions or Limitations	☐ High	☒ Moderate	☐ Slight
13	Simplicity and Reliability	☐ Poor	☐ Fair	☒ Good
14	Unattended Operation	☐ No		☒ Yes
15	Maintenance Requirements	☐ High	☐ Medium	☒ Low
16	Adverse Ambient Effects	☐ High	☒ Moderate	☐ Slight
17	Submersion Proof	☐ No		☐ Yes
18	Ruggedness	☐ Poor	☐ Fair	☒ Good
19	Self Contained	☐ No		☒ Yes
20	Precalibration	☒ No		☐ Yes
21	Ease of Calibration	☐ Poor	☒ Fair	☐ Good
22	Maintenance of Calibration	☐ Poor	☒ Fair	☐ Good
23	Adaptability	☐ Poor	☐ Fair	☐ Good
24	Cost	☐ High	☐ Medium	☒ Low
25	Portability	☒ No		☐ Yes